CR-171713
15958-T-1548-MA-129T-003F
C.1

(NASA-CR-171713) COMBUSTION PERFORMANCE AND HEAT TRANSFER CHARACTERIZATION OF LOX/HYDROCARBON TYPE PROPELLANTS, VOLUME 1 Final Report (Aerojet Liquid Rocket Co.) 142 p HC A07/MF A01 CSCL 21I G3/28

N84-11319

Unclas
42477

COMBUSTION PERFORMANCE AND HEAT TRANSFER CHARACTERIZATION OF LOX/HYDROCARBON TYPE PROPELLANTS

Final Report

Volume I

April 1983

Prepared For:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lyndon B. Johnson Space Center
Contract NAS-9-15958

Prepared By:

AEROJET LIQUID ROCKET COMPANY

Report 15958T-1548-MA-129T-003F

April 1983

Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants

Contract NAS 9-15958

FINAL REPORT

Volume I

Prepared For:

NASA-Lyndon B. Johnson Space Center
Houston, Texas

Prepared By:

R. W. Michel

R. W. Michel

Approved By:

R. W. Michel

R. W. Michel

Aerojet Liquid Rocket Company
P.O. Box 13222
Sacramento, California 95813

FOREWORD

The Aerojet Liquid Rocket Company (ALRC) submits this report as a part of the Contract NAS 9-15958, Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants.

The program was conducted for the NASA-Johnson Space Center under the cognizance of M. F. Lausten and W. C. Boyd, technical monitors. ALRC management included J. W. Salmon and R. W. Michel, program managers, and R. S. Gross, L. Schoenman, and S. W. Hart, project engineers for Tasks I, II, a d III, respectively.

Supporting ALRC personnel include:

<u>Analysis</u>: S. Bucella, R. L. Ewen, J. C. Fang, G. M. Meagher, J. L. Pieper, R. L. Sabiers, C. F. Taylor, W. R. Thompson, R. E. Walker

<u>Design</u>: L. L. Lang, D. E. Lemke, K. Y. Wong

<u>Test</u>: B. W. Cathroe, A. R. Keller, R. J. Pruett, D. C. Rousar

PRECEDING PAGE BLANK NOT FILMED

ABSTRACT

This program, Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants, Contract NAS 9-15958, was undertaken to evaluate liquid oxygen and various hydrocarbon fuels as low cost alternative propellants suitable for future space transportation system applications. The emphasis of the program is directed toward low earth orbit maneuvering engine and reaction control engine systems.

The feasibility of regeneratively cooling an orbit maneuvering thruster was analytically determined over a range of operating conditions from 100 to 1000 psia chamber pressure and 1000 to 10,000-lbF thrust, and specific design points were analyzed in detail for propane, methane, RP-1, ammonia, and ethanol; similar design point studies were performed for a filmcooled reaction control thruster.

Heat transfer characteristics of propane were experimentally evaluated in heated tube tests. Forced convection heat transfer coefficients were determined over the range of fluid conditions encompassed by 450 to 1800 psia, -250 to +250°F, and 50 to 150 ft/sec, with wall temperatures from ambient to 1200°F, and heat fluxes to 10 Btu/in.^{2}sec. Nucleate boiling and coking were also evaluated.

Seventy-seven hot firing tests were conducted with LOX/propane and LOX/ethanol, for a total duration of nearly 1400 seconds, using both heat sink and water-cooled calorimetric chambers. Combustion performance and stability and gas-side heat transfer characteristics were evaluated. Four injectors were tested: two with conventional like-on-like doublet and OFO triplet elements, and two with unconventional platelet elements. Film cooling was also assessed. The combustion chamber was sized for a nominal thrust of 1000-lbF at 300 psia chamber pressure, and testing spanned a significant range of chamber pressure and propellant mixture ratio conditions.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. PROGRAM OBJECTIVES

The objectives of this program were to evaluate and characterize candidate liquid oxygen/hydrocarbon fuel combinations, and to establish a technology base for these propellants that would guide the selection of hydrocarbon fuels in future space transportation system applications.

While the program results are pertinent to any size liquid rocket engine, the program was directed toward that thrust range representative of the current Reaction Control System (RCS) and Orbit Maneuvering System (OMS) engines on the Space Shuttle.

The current RCS and OMS propellants -- nitrogen tetroxide and monomethyl hydrazine -- have several drawbacks: high cost, potential unavailability due to limited manufacture, formation of carcinogenic intermediates during manufacture, toxicity, handling difficulties, and associated handling requirements.

The current storable propellant combination was selected over liquid oxygen/liquid hydrogen, which offered much higher performance but was constrained by the volume requirements of the fuel, as well as over liquid oxygen/hydrocarbon fuel alternatives, for which the technology base was generally lacking. The storable propellants had a large technology base, and the simple pressure-fed engine systems promised high reliability and minimal development cost.

Engine development cost and recurring operational costs are key factors in the overall cost of a space transportation system. Low-cost easily handled propellants, typified by oxygen/hydrocarbons, and reusable engine systems combine to minimize operational costs. Development costs can, in part, be minimized by the judicious selection of the propellants; that selection presupposes a substantial technology base. The intent of this program is to contribute to such a base.

B. PROGRAM SUMMARY

The program was conducted over a forty month period, beginning in October 1979. It consisted of three major task areas; as described below. These task areas are documented in three comprehensive data dumps, References (1), (2), and (3). This final report is in two volumes. Volume I presents Tasks I and III; Volume II presents Tasks II and IV.

TASK I - REGENERATIVE COOLING CHARACTERIZATION

This task comprised two subtasks. First, forced convection and nucleate boiling heat transfer data and correlations available in the literature for

candidate hydrocarbon fuels were reviewed. These candidates included propane, methane, RP-1, and ammonia. Regenerative chamber cooling analyses were then conducted to compare the cooling capabilities of each fuel and determine the operating point (thrust and chamber pressure) limits imposed thereby. Second, heated tube tests were performed to determine the heat transfer characteristics and the coking behavior of propane, both commercial grade and instrument grade.

TASKS II AND IV - SUBSCALE INJECTOR CHARACTERIZATION

Tasks II and IV involved the design, fabrication, testing and data analysis of subscale hardware, i.e., nominal thrust of 1000-lbF, to evaluate the combustion performance, stability, and gas-side heat transfer characteristics of liquid oxygen/hydrocarbon propellants. Four injector patterns were tested, including conventional OFO triplets and like-on-like doublets, and unconventional platelet patterns in which fuel swirler elements were located within pairs of drilled orifice or splashplate oxidizer elements. Heat sink and water-cooled calorimeter chambers were utilized, and a removable chamber section was used with the former to allow evaluation of chamber length effects. A fuel film coolant ring was used in conjunction with the triplet and platelet injectors. An adjustable accoustic cavity section provided combustion stability.

Seventy-seven tests were conducted, with a total duration of approximately 1370 seconds. Both propane and ethanol were tested, the latter with gaseous as well as liquid oxygen. Chamber pressure and mixture ratio were varied widely to assess operating point effects.

TASK III - PRELIMINARY ENGINE SYSTEM CHARACTERIZATION

In Task III numerous engine operating points were analyzed to determine engine performance and weight figures for orbit maneuvering and reaction control system thrusters. The work built upon the regenerative cooling studies of Task I, updated for the propane heat transfer correlation derived empirically in that task, and extended to include turbomachinery for pump-fed systems, alternative chamber materials for the orbit maneuvering thruster, and film cooling for the reaction control thrusters. Thruster envelopes were defined by the current engines on the Space Shuttle.

C. PROGRAM CONTRIBUTIONS TO NASA OBJECTIVES

This program significantly enlarges the technology base for LOX/Hydrocarbon propellants and is an important step towards a LOX/Hydrocarbon axuiliary propulsion system. A number of additional steps is obviously necessary for that system to become a reality.

Specific results and conclusions developed in the program are summarized below. The extensive experience gained in the design, analysis, and testing of hardware for these propellants also contributes to the technology base but cannot be readily quantified.

Hot fire testing went smoothly and was quite successful. High combustion performance was achieved with conventional as well as unconventional injector elements and stable combustion was readily obtained with acoustic cavities. However, chamber gas-side heat fluxes were considerbly higher than values based on standardized predictive methods. Apart from this, there were no big surprises, and the design of high performance, stable, regeneratively-cooled thrust chambers does not appear to present any unusual or insurmountable difficulties.

Perhaps the biggest disapppointment -- in terms of using LOX/hydrocarbon propellants for the APS was the low wall temperature threshold determined for coking of propane. This, combined with propane's incompatibility with copper, the material of choice for high pressure regeneratively cooled chambers because of its high thermal conductivity, may eliminate propane as a candidate propellant. This would be unfortunate, because propane otherwise offers a desirable combination of high combustion performance and high mass density.

On the analytical side, the engine point designs generated in this program, in conjunction with the system point design studies conducted in Reference (4) -- to which the Task III results were input -- strongly support any future selection of propellant, operating point, engine cycle, and degree of system integration. The approach here was to first consider the flow and pressure drop requirements of the thrust chamber and injector and then work upstream to the turbopump requirements and/or tank conditions, overall engine performance and weight, and finally in the Reference (4) program to system optimization.

II. RESULTS AND CONCLUSIONS

A. TASK I - REGENERATIVE COOLING CHARACTERIZATION

1. The parametric regenerative cooling analysis showed the following for the four candidate fuels:

(a) Methane: either vapor phase or supercritical pressure fluid is an acceptable coolant at higher thrust levels over the entire range of chamber pressure without the need for additional film-cooling. Subcritical pressures are unacceptable because of the limited subcooling.

(b) Propane: either vapor phase or supercritical pressure fluid is acceptable at higher thrust levels without additional film cooling. Subcritical pressures are unacceptable because of low burnout heat flux.

(c) RP-1: because of low coking temperature, RP-1 is not a satisfactory coolant.

(d) Ammonia: either liquid (nucleate boiling) or vapor phase is acceptable.

2. Sufficient heat can be picked up in the nozzle to vaporize the fuel -- in the case of methane and propane only -- to allow vapor-phase cooling of the combustion chamber.

3. Heated-tube testing of propane resulted in a forced convection correlation that grouped 95% of the data within $\pm 24\%$. Limited film and nucleate boiling data were obtained; burnout heat flux was found to be considerably higher than an extrapolation of available low flux data would predict.

4. Coking in the heated tube tests occurred at wall temperatures less than 500°F; coking rate was comparable to published data for RP-1. Propane purity affected the rate but not the threshold temperature of coking.

B. TASKS II AND IV - SUBSCALE INJECTOR CHARACTERIZATION

1. The like-on-like injector pattern was fired with LOX/propane in a heat-sink chamber and found to be low-performing, as a result of both poor atomization and poor mixing. The combustion was bomb-stable.

2. The OFO triplet injector was fired with both LOX/propane and LOX/ethanol in both heat-sink and water-cooled calorimeter chambers. In the calorimeter chamber it was tested with and without fuel film-cooling. Performance was very high with LOX/propane, for which the unit was designed, and slightly lower with LOX/ethanol due to non-optimum propellant momentum match. Combustion was stable with both propellant combinations.

3. One platelet injector was designed for liquid-phase injection of LOX/ethanol; the injector pattern consisted of a swirler fuel element within two splashplate oxidizer elements. Although this unit achieved high performance, propellant blowapart apparently occurred, causing the outer periphery to be oxidizer-rich. The addition of fuel film-coolant increased the gas-side heat flux as well as injector performance.

4. The other platelet injector was designed for gaseous oxygen (GOX)/ethanol injection. The pattern consisted of a fuel swirler element within two drilled oxidizer orifices. This injector achieved high performance with ambient temperature propellant and slightly reduced performance at [illegible] (-130°F) temperature.

5. Throat heat fluxes experienced with ethanol were considerably high[illegible] than would be predicted with the standardized pipe-flow correla[illegible]n. [illegible] inferred correlating coefficient (Cg) was approximately 70% [illegible] than would be expected for storable propellants. The correlat[illegible]ent for ethanol was found to be extremely sensitive to mixt[illegible]atio.

6. Carbon deposition in the acoustic cavities with LOX/propane was extensive to the point that acoustic damping capabilities could be lost. Film-coolant injection from the forward end of the cavities reduced the amount of carbon deposition within the cavities.

7. Carbon deposition on the chamber wall occurred only with LOX/propane and was largely lost during the start and/or shutdown transients. Engine restart was marked by a return to clean-wall heat flux conditions, followed by a progressive decay as the deposition layer increased. As a result, the thermal resistance of the deposition layer cannot be assumed for design purposes to limit gs-side wall temperatures to less than clean-wall values.

8. Carbon deposition was negligible with LOX or GOX/ethanol. The exhaust plume was clear whereas with LOX/propane it was not.

C. TASK III - PRELIMINARY ENGINE SYSTEM CHARACTERIZATION

1. Design point analyses for ten different concepts (propellant combinations and operating points) involving a pressure-fed regeneratively-cooled orbit maneuvering engine showed the following:

(a) Methane, with vapor-phase cooling, offers the highest specific impulse.

(b) Propane performance, with vapor-phase cooling, is nearly as high but is severely degraded with liquid-phase cooling due to high film-cooling requirements.

(c) Ethyl alcohol requires no film cooling but the performance is lower than that of liquid propane.

2. Analyses of twenty-eight concepts involving a pump-fed, regeneratively-cooled orbit maneuvering engine showed the following:

(a) The highest performance is again obtained for methane.

(b) Performance with propane is slightly lower.

(c) Performance of all twelve methane and propane concepts is within a range of 10 sec Isp, over a large range of thrust and chamber pressure.

(d) Ethyl alcohol performance is lower than that of methane or propane, and the performance of ammonia is only slightly higher than that of a pressure-fed storable propellant engine.

(e) In light of the propane/copper compatibility issue, nickel was examined as an alternative (to copper) chamber wall material and is found suitable to about 400 psia chamber pressure without the use of film-cooling.

(f) Regenerative cooling with liquid oxygen is feasible at high chamber pressures, if required because of fuel-cooling limitations.

(g) Subcooling the propane could eliminate the need for boost pumps.

3. Analyses of twelve concepts for the film cooled reaction control engine and vernier engine showed the following:

(a) The trend of performance for the candidate fuels is similar to that for regeneratively cooled thrusters: methane, propane, ethyl alcohol, and ammonia.

(b) Film-coolant requirements center around 20% of the fuel for the reaction control thruster regardless of fuel or chamber pressure.

III. RECOMMENDATIONS

A. Investigate the causes of propane coking -- impurities, catalytic effects, etc.

B. Develop solutions to the incompatibility of propane and copper, such as coatings, alloys, fuel additives, etc.

C. Characterize coking thresholds and heat transfer of methane and ethanol.

D. Develop correlations for gas-side soot formation of LOX/methane and LOX/propane.

E. Characterize gas-side heat transfer for these propellants (typically higher heat transfer rates are measured than would be predicted with standard formulations). Also, characterize film-cooling behavior.

F. Address fuel-rich combustion behavior as applicable to gas generator and turbopump devices.

G. Evaluate the cost aspects and systems issues (handling, etc.) associated with LOX/hydrocarbon propellants.

H. Pursue the explanation for anomalous behavior observed during testing: (1) the requirement for higher oxidizer-to-fuel momentum ratios to achieve optimum performance in hot-fire tests than would be predicted on the basis of cold-flow test results; (2) the exceptionally high throat heat fluxes observed in the ethanol firings; (3) the increased carbon deposition effect noted with LOX/propane at higher mass flux (chamber pressure).

IV. TECHNICAL DISCUSSION

A. TASK I - REGENERATIVE COOLING CHARACTERIZATION

Task I comprised two subtasks, which are discussed separately. These subtasks are:

Task I.1 - Cooling Correlation and Comparison
Task I.2 - Experimental Heat Transfer Investigation

B. TASK I.1 - COOLING CORRELATION AND COMPARISON

1. Objectives

The objectives of Task I.1 were to:

(a) Conduct a literature review of the cooling characteristics of propane, methane, RP-1, and ammonia.

(b) Determine the feasibility of regenerative cooling for the four fuels over a range of thrust from 1000 to 10,000-lbF and a range in chamber pressure from 100 to 1000 psia.

(c) Specify operating conditions for which heated-tube testing is required to characterize or corroborate heat transfer behavior of the four fuels.

2. Scope

Numerous point studies were made to determine regenerative cooling feasibility at various thrust levels, chamber pressures, and coolant states. The following table provides an overview of the scope of these point studies:

Coolant	Coolant State	# Cases	# Thrust Levels	# Chamber Pressures
Propane	Supercritical Pressure	16	4	4
Propane	Subcritical Pressure - Vapor	24	4	5
Propane	Subcritical Pressure - Liquid	11	2	2
Methane	Supercritical Pressure	6	4	4
Methane	Subcritical Pressure - Vapor	6	4	3
RP-1	Supercritical Pressure	6	2	2
RP-1	Subcritical Pressure - Liquid	1	1	1
Ammonia	Subcritical Pressure - Liquid	4	3	3

3. Approach

The seventy-four cases above were analyzed with the SCALER Computer Program for forced convection cases and with a modified version of the program, BOSCALE, for nucleate boiling cases. These two programs were developed by ALRC specifically for parametric design studies. With the programs it is economic to generate a relatively large number of point studies and still obtain a detailed multi-station analysis of a rectangular channel at each axial station.

The SCALER program scales the chamber geometry and the local gas-side heat transfer coefficients and coolant heat loads from reference input to other thrust and chamber pressures. The coolant channel geometry parameters are prescribed together with channel material(s) and their temperature-dependent properties and the coolant-side heat transfer correlation(s). Two-dimensional heat conduction around the coolant channel is included providing a fin effectivity which results in a transformation of the gas-side heat flux to a lower-valued coolant-side flux. At each station, the program iterates to determine the channel depth required for satisfying (1) a gas-side wall temperature limit, which can be specified as a function of closeout wall temperature with cycle life and creep criteria, and (2) an optional coolant-side wall temperature limit, such as the coking temperature of the coolant. The only simplifying assumption is that gas-side wall temperature differences between the reference input and the scaled cases have a negligible effect on gas-side heat transfer coefficients and heat loads. Normally, gas-side wall temperature limits are well-known in advance, so that local reference gas-side heat transfer analyses can be run at appropriate wall temperatures.

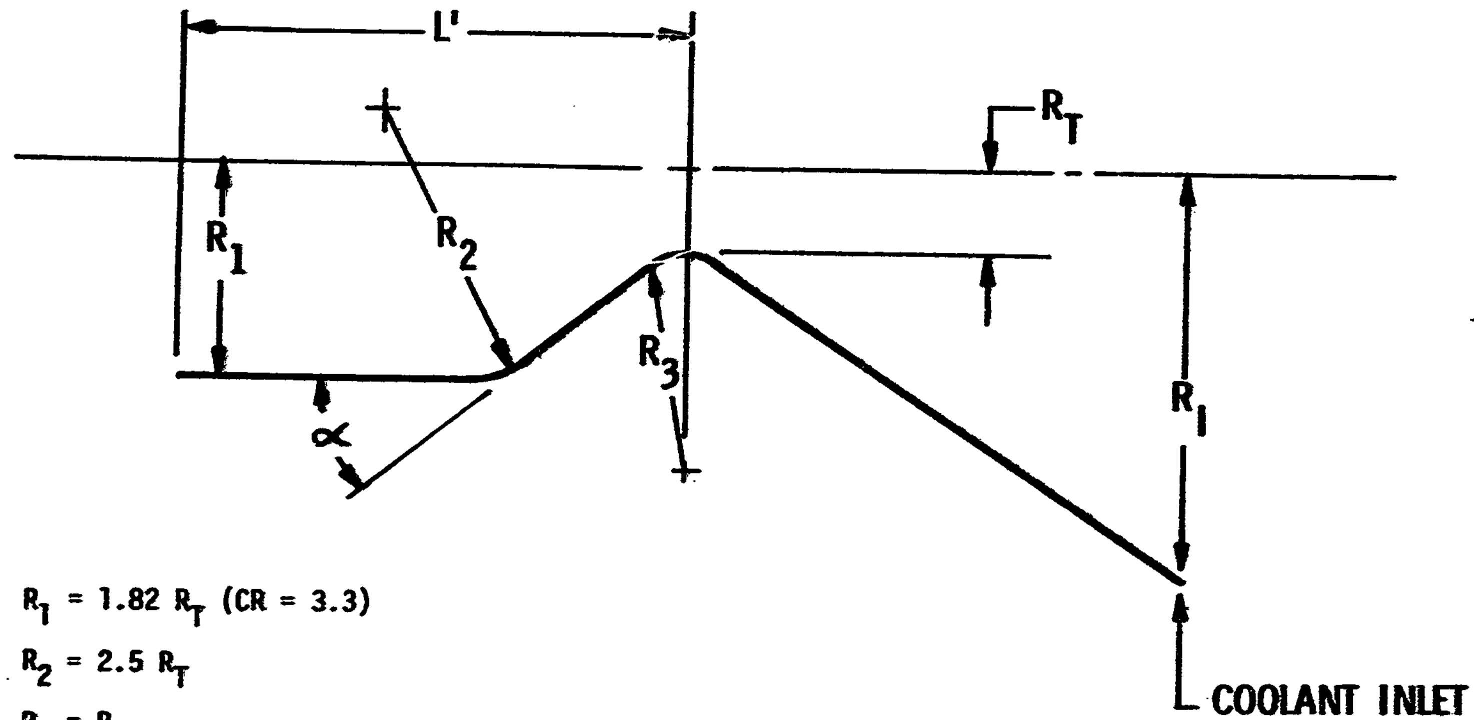
The BOSCALE program was written during this study to include subcooled nucleate boiling and burnout heat flux as parameters. The program defines the coolant velocity required at an axial station on the basis of a specified burnout safety factor. Iteration on channel depth thus satisfies both the gas-side wall temperature limit, as in SCALER, as well as the coolant-side heat flux limit.

4. Groundrules and Assumptions

a. Thrust Chamber Design

The thrust chamber geometry assumed for all point designs is illustrated in Figure 1. Chamber length (l') was taken to be 10 to 11 in. The nozzle contour is that of a 400:1 area ratio 90% bell nozzle. The regeneratively cooled section extends to the point of maximum allowable temperature (2755°F) for a coated columbium skirt based on 15 hour life considerations. The attachment area ratio is calculated from a simple energy balance:

● TCA GEOMETRY



$R_1 = 1.82\ R_T$ (CR = 3.3)

$R_2 = 2.5\ R_T$

$R_3 = R_T$

R_I (COOLANT INLET) = 20 IN. (OMS), 10 IN. (RCS), RADIATION ATTACHMENT POINT

$\alpha = 30°$

NOZZLE CONTOUR = RAO 90% BELL

$L' \cong 19$ INCH

Figure 1. Thrust Chamber Contour

$$hg\ (T_r - T_{wg}) = \sigma\epsilon\ (1 + f)\ T_{wg}^4$$

where hg is the heat transfer coefficient, T_r and T_{wg} are the recovery and wall temperatures, σ is the Stephan-Boltzman constant, ϵ is the emissivity, and f is the internal view factor to the nozzle exit plane.

b. Coolant Channel Design

A typical rectangular coolant channel layout is shown in Figure 2. Normally, each set of input parameters (i.e., inlet pressure and bulk temperature) requires an iterative optimization of station channel and land dimensions to minimize pressure drop and provide the most effective cooling. Such an optimization was beyond the scope of this parametric study but several channel designs were utilized as approximations for the needs of a broad categorization of heat transfer regimes and coolant states (e.g., dense single-phase supercritical superheated vapor, etc.). Configuration details of these channel designs are summarized on Table I.

In order to minimize maldistribution of flow resulting from typical dimensional tolerances, a channel depth of 0.030 in. was selected as the minimum representative of a feasible channel design. Channel depths of 0.020 to 0.030 in. were considered marginal in that, with optimization, satisfactory minimum depths of 0.020 in. might be obtained. Channel depths less than 0.020 in. were considered beyond improvement to the minimum depth.

For the hydrocarbon fuels, zirconium copper (Zr-Cu) was selected as the gas-side liner material, with an electroformed nickel outer wall. Because of the incompatibility of ammonia and copper, 304L stainless steel was selected for the ammonia design cases. Gas-side wall temperature limits for Zr-Cu were set by Figure 3, which is based on creep and cycle life considerations; gas-side wall thickness requirements were based on Figure 4. Similar design charts were used for 304L stainless steel.

c. Gas-Side Heat Transfer

Throat Reynolds numbers in this study covered a range which yields three boundary layer flow regimes. At high Reynolds number the flow is fully turbulent; at low Reynolds number, acceleration effects are strong enough to cause the boundary layer to undergo reverse transition to laminar flow. At moderate Reynolds number, the transition process is started but not completed in the convergent section; the transition process spans the Reynolds number range of 6 to 13 x 10^5. Figure 5 displays the the three flow regimes over the thrust chamber pressure map of interest to this study.

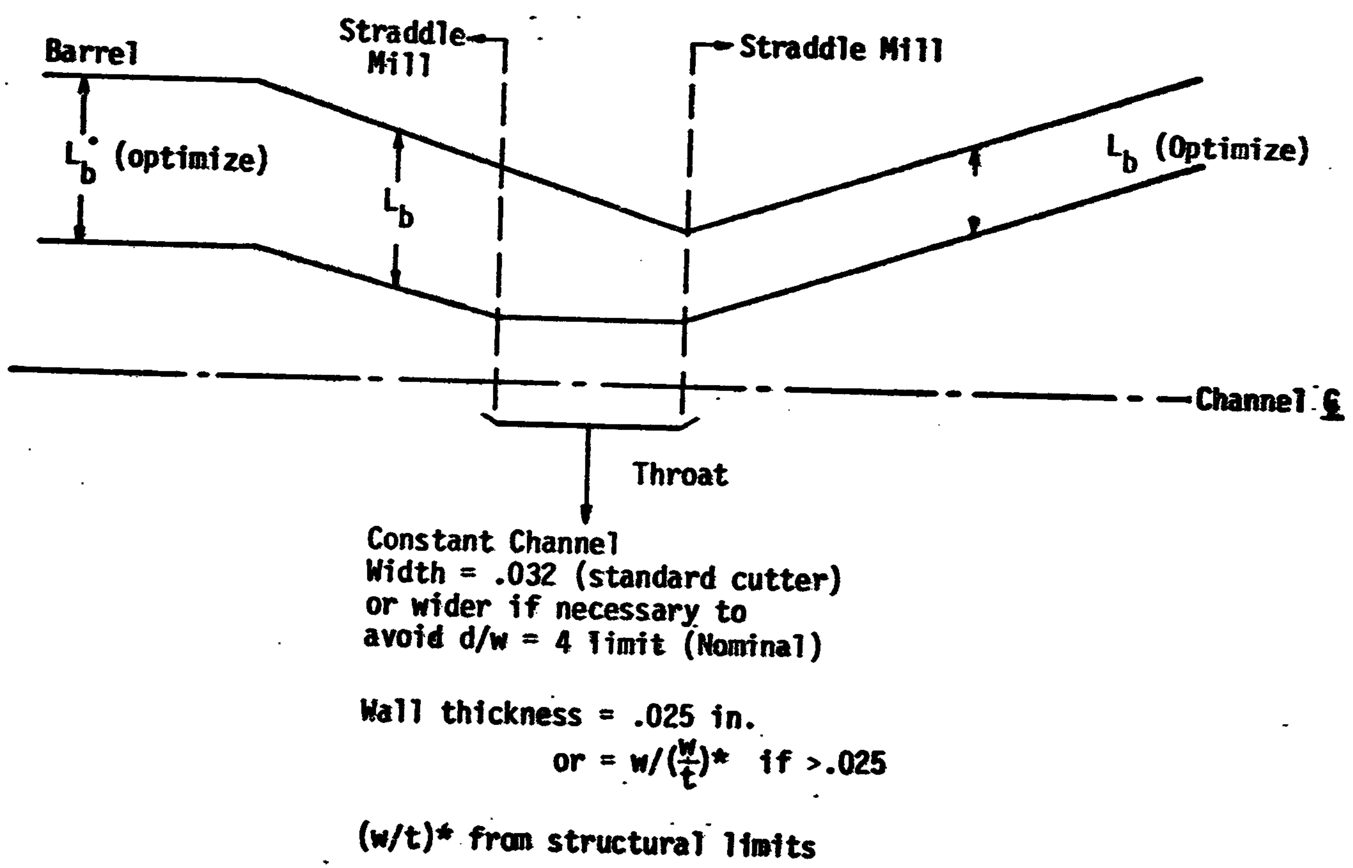


Figure 2. Channel Layout

TABLE I

CHANNEL DESIGN LAYOUT

Station	A/A_t	A Channel Controlling Dimensions: Channel Width, in.	A Channel Controlling Dimensions: Land Width, in.	A′ Channel Controlling Dimensions: Channel Width, in.	A′ Channel Controlling Dimensions: Land Width, in.	A" Channel Controlling Dimensions: Channel Width, in.	A" Channel Controlling Dimensions: Land Width, in.	C Channel Controlling Dimensions: Channel Width, in.	C Channel Controlling Dimensions: Land Width, in.	D Channel Controlling Dimensions: Channel Width, in.	D Channel Controlling Dimensions: Land Width, in.
1	208.7	.174		.174		.130		.174			.120
2	189.6										
3	161.0										
4	133.0										
5	105.1										
6	88.1										
7	69.2										
8	52.6										
9	41.8										
10	30.9										
11	22.8										
12	16.1										
13	11.0										
14	6.73		.030		.030		.030		.080		
15	3.77										
16	2.21										
17	1.16										
18	1.00	.0324		.0325		.0325					
19	1.07							.070		.040	
20	1.29										
21	1.71		.040								
22	2.20						.040		.080	.060	
23	2.65									.088	
24	3.00									.166	
25	3.30										.150
26	3.30										
27	3.30										
28	3.30										
29	3.30										
30	3.30										
31	3.30										
32	3.30										
33	3.30										
34	3.30										
35	3.30										
36	3.30										
37	3.30										

ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

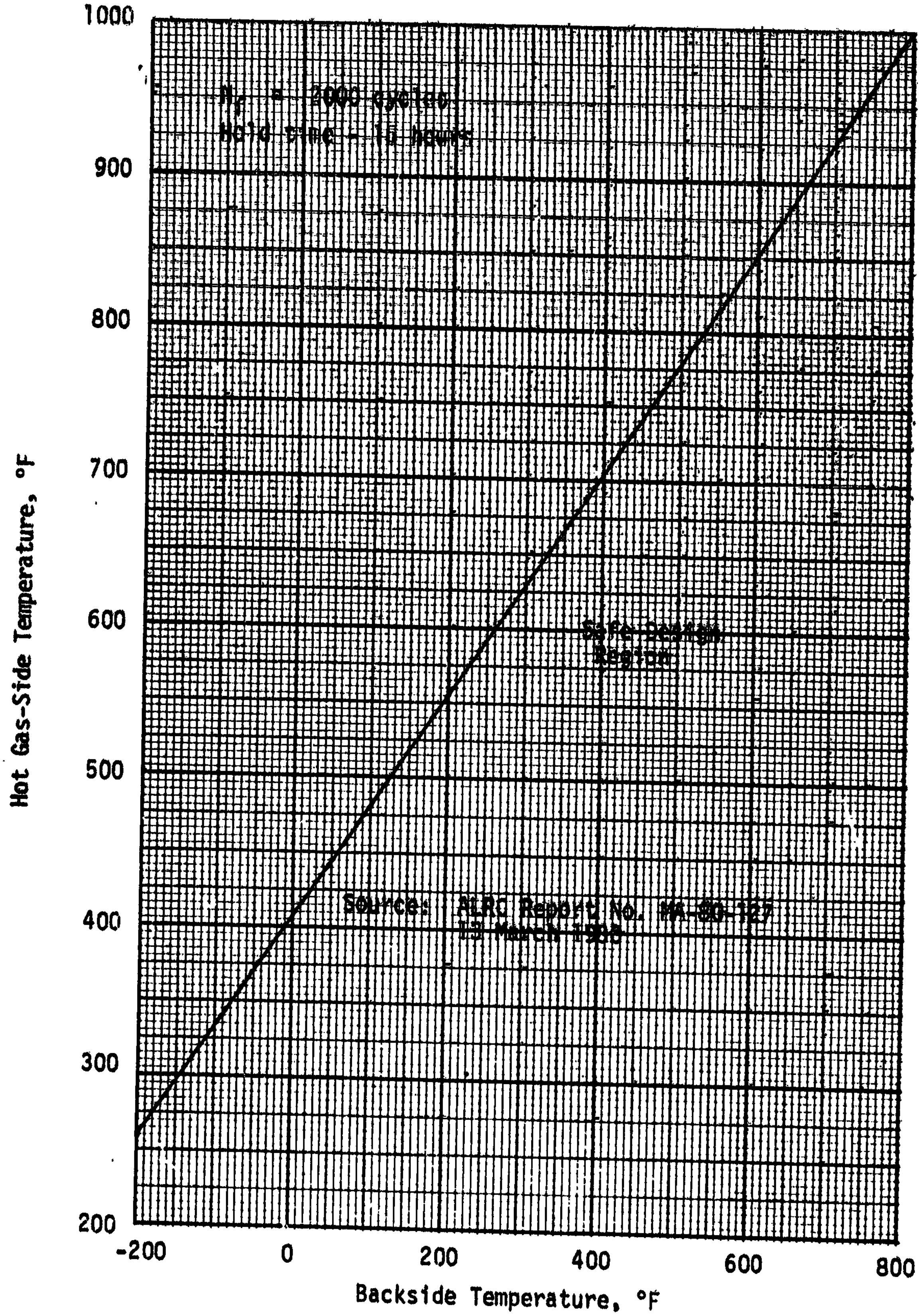


Figure 3. Zr-Cu Wall Temperature Limits

ORIGINAL PAGE IS
OF POOR QUALITY

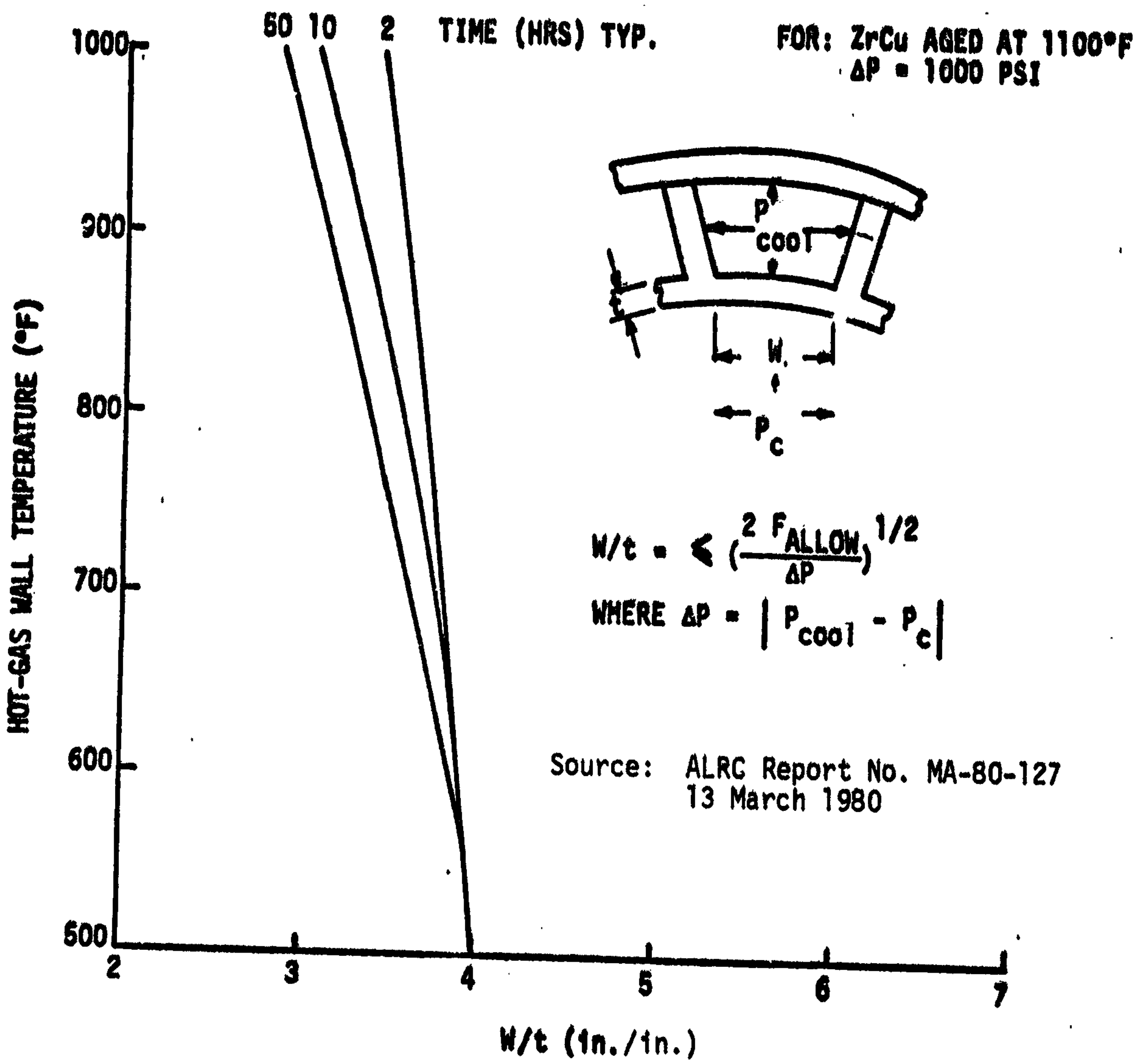


Figure 4. Zr-Cu Chamber Wall Thickness Requirements

ORIGINAL PAGE IS
OF POOR QUALITY

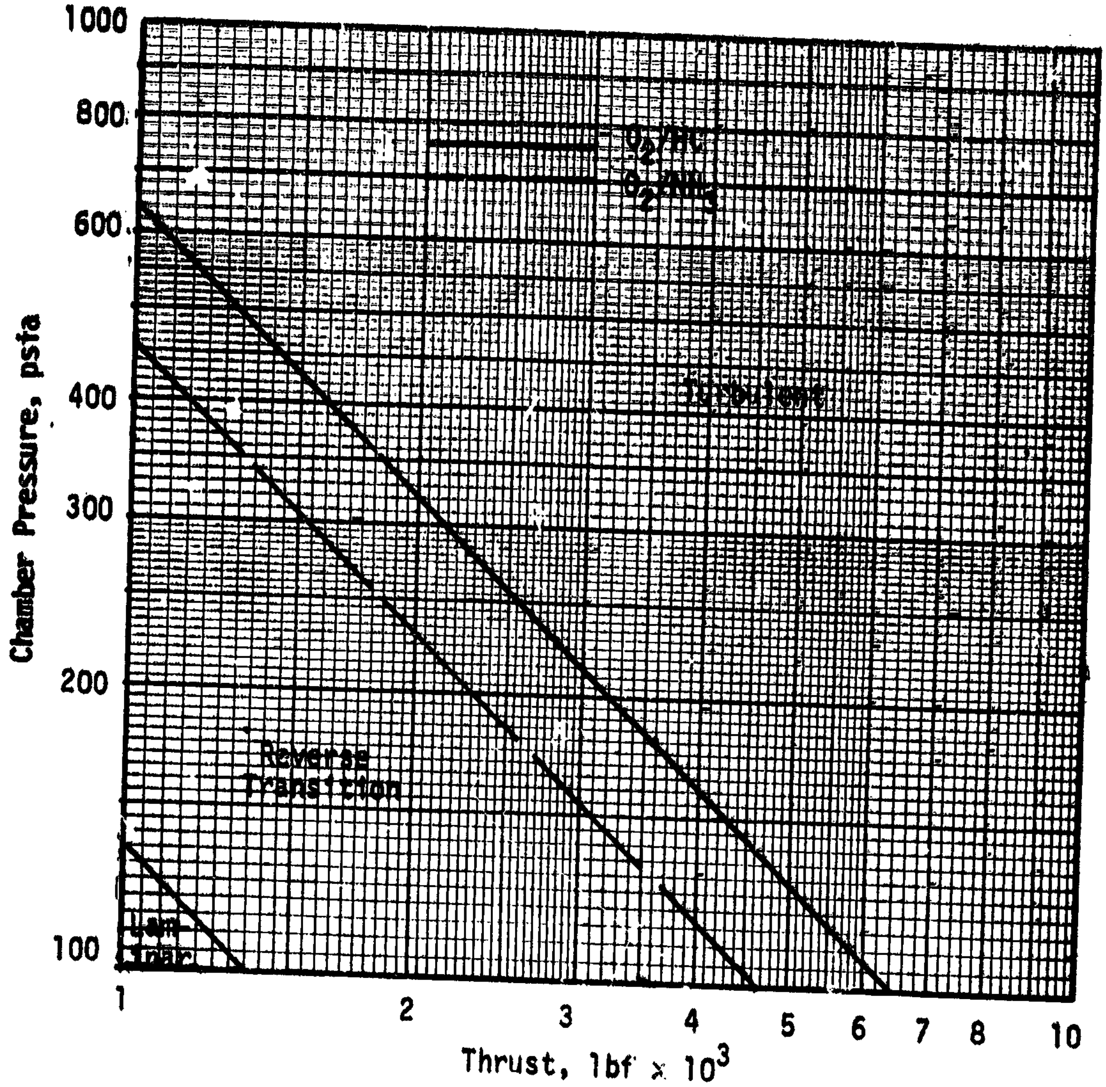


Figure 5. Gas-Side Boundary Layer Flow Regimes

In the fully turbulent regime, the heat transfer coefficient was calculated from the standard pipe flow correlation, as illustrated by Figure 6. The decrease in the correlating coefficient represents the effects of flow acceleration. In the laminar flow regime, a laminar heat transfer correlation was used, and in the transition region, the laminar and turbulent heat transfer coefficients were weighted on the basis of throat Stanton numbers based on laminar and turbulent formulations.

Heat flux reduction due to carbon deposition on the gas-side was accounted for by a factor that was used only for calculation of the coolant bulk temperature rise and not for calculation of local wall temperatures (due to potential local spalling of the deposition layer). The following multiplying factors were used:

Methane:	0.765
Propane:	0.42
RP-1:	0.25
Ammonia:	1.00

The factors for the hydrocarbon fuels were based on the hydrogen/carbon ratio, following the approach of Reference 5; a value of 1.0 (no reduction) was also evaluated for the hydrocarbon fuels.

d. Coolant-Side Heat Transfer

Forced convection of methane and propane at supercritical pressures was represented by the correlation developed by ALRC for supercritical oxygen (Ref. 6).

$$Nu_b = 0.025\, Re_b\, Pr_b^{0.4} \left(\frac{\rho_b}{\rho_w}\right)^{0.5} \left(\frac{K_b}{K_w}\right)^{0.5} \left(\frac{\bar{C}_p}{C_{p_b}}\right)^{0.67} \left(\frac{P}{P_{crit}}\right)^{-0.2} \left(1 + \frac{2}{\ell/D}\right)$$

All other forced convection situations were represented by the Hines equation (Ref. 7):

$$Nu_b = 0.005\, Re_b^{\ 0.95}\, Pr_b^{\ 0.4}$$

The burnout heat flux correlations for propane, based on Reference 8 and derived by ALRC were:

$$\phi_{BO} = 0.3 + 0.0004\ V\,\Delta T_{sub}, \qquad V\,\Delta T_{sub} \le 1000$$

$$= 0.58 + 0.00012\ V\,\Delta T_{sub}, \qquad V\,\Delta T_{sub} > 1000$$

ORIGINAL PAGE IS
OF POOR QUALITY

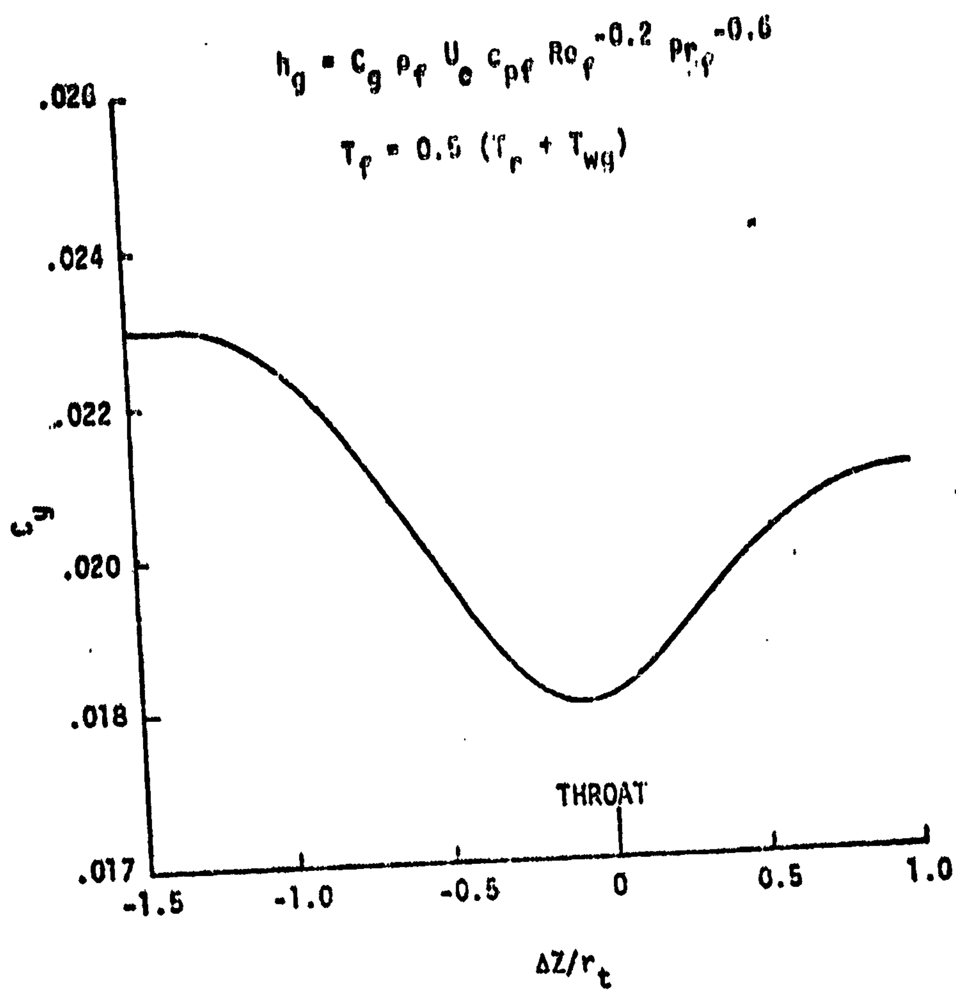


Figure 6. Gas-Side Heat Transfer - Turbulent Regime

where:

V = coolant velocity, ft/sec
ΔT_{sub} = coolant subcooling, °F
ϕ_{BO} = burnout heat flux, Btu/in.^{2} sec

These correlations were supported by limited empirical data to:

$$V\,\Delta T_{sub} = 3600\,°F\ \text{ft/sec, with a spread of} \pm 25\%.$$

The burnout heat flux correlations for ammonia, based on References 9 and 10, and developed by ALRC, were:

$$\phi_{BO} = 2.15 + 0.00086\,V\,\Delta T_{sub}, \qquad V\,\Delta T_{sub} \leq 4000$$

$$= 3.3 + 0.000587\,V\,\Delta T_{sub}, \qquad T_{sub} > 4000$$

These correlations are supported by data to $V\,\Delta T_{sub}$ = 14,000°F ft/sec, with a spread of ±30%.

Coolant-side wall temperatures were limited by coking considerations to the following values:

Propane: 800°F
Methane: 1300°F
RP-1: 550°F

5. <u>Results</u>

Results for the various point designs are displayed graphically on Figure 7 and summarized on Tables II through VIII. Figure 8 defines the locations of temperatures and flux values identified on the tables.

Figure 9 compares the heat available in the nozzle to that required to vaporize all or part of the fuel so that the vapor-phase fluid can be made available for cooling the combustion chamber. The intricacies of the coolant state change in the nozzle were not addressed.

C. TASK I.2 - HEATED TUBE TESTS

1. <u>Objectives</u>

The objectives of the heated tube testing were to (a) correlate the forced convection behavior of sub- and supercritical pressure propane; (b) determine the nucleate boiling and burnout heat flux characterization of subcritical pressure propane; (c) investigate propane coking characteristics at elevated wall temperatures.

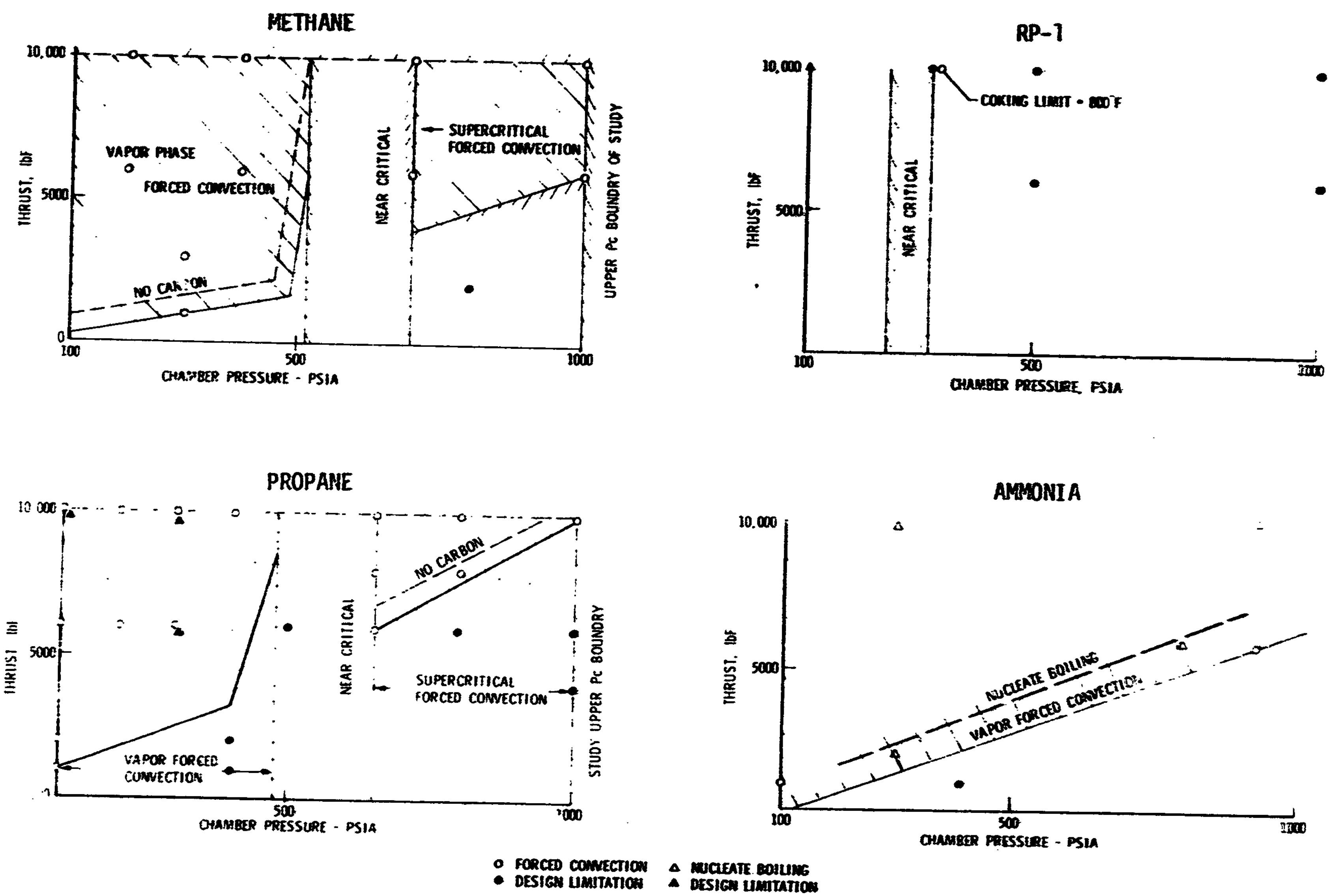


Figure 7. Cooling Feasibility Map

TABLE II

PROPANE AT SUPERCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc psia	P_{in}/P_c -	$\dot{P}_{in}$ psia	T_{in} °F	Carbon Factor	T_{coke} °F	Corre-lation	ε -	Engine Basis	Channel Design	Computer Run Ident.
7A-1.1	10K	1000	1.8	1800	-44	.42	750	LOX	Rad.Attach.	OMS	A	7A/2-11/1
-1.2		800		1440		1.0	800					7A/2-13/1
-1.3		650		1170		.42	750					7A/2-11/1
-2.1	8K	800		1440		.42	800					7A/2-13/1
-2.2		650		1170		1.0	750					7A/2-12/1
-3.1	6K	1000		1800		.42	750					7A/2-11/1
-3.1A		1000		1800			800				A'	7A/2-14/1
-3.2		650		1170			750				A	7A/2-11/1
-3.2A		650		1170			800					7A/2-13/1
-3.3		500		900			800					7A/2-13/1
-4.1	4K	1000		1800			750		155			7A/2-11/1
-10.1	10K	1000		1800	-295				Rad.Attach.			7A/2-12/1
-11.1	6K	1000		1800		1.0						7A/2-12/2
-11.1A		1000		1800		.42						7A/2-12/2
-11.2		800		1440								7A/2-12/2
-11.3		650		1170			800					7A/2-13/1

ORIGINAL PAGE IS OF POOR QUALITY

TABLE II (CONT.)

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loca. ε	Design Limit Type -	Design Limit Loca. -	Rad. Attach ε	T @ Throat °F	V @ Throat ft/sec
7A-1.1	1000	1.262	6.85	129	-10.78	.385	234	136	.08	L'	.032	1.0	Coking	TM2	33.1	27	133
-1.2	800	1.410		144	-10.96	.410	415	371	.26		.030	-1.97			26.5	98	108
-1.3	650	1.565		160	-11.14	.245	200	157	.05		.035	-2.18			21.2	11	66
-2.1	800	1.262	5.48	129	-10.78	.348	232	189	.07		.028	-2.15			27.1	20	94
-2.2	650	1.400		143	-10.94	.552	406	362	.32		.025	-1.95			21.7	83	80
-3.1	1000	.977	4.11	101	-10.45	.803	272	229	.22		.019	-3.3			35.0	30	140
-3.1A	1000	.977		101	(-7.73)	(1.104)	(230)	(187)	(.25)		.025	L'			35.0	30	140
-3.2	650	1.212		124	-10.72	.540	235	191	.10		.022	L'			22.2	14	80
-3.2A	650	1.212		124	-10.72	.449	236	192	.09		.023	-2.65			22.2	14	76
-3.3	500	1.382		141	-10.92	.398	222	179	.07		.025	-2.65			17.1	15	60
-4.1	1000	.798	2.74	83	(-.49)	(.467)	(153)	(110)	(.13)	ε = -1.37	.015	-1.37			N/A	94	175
-10.1	1000	1.262	6.85	129	-10.78	.372	291	-3	.03	ε = 1.0	.029	-1.39			33.1	-212	169
-11.1	1000	.977	4.11	101	-10.45	.961	656	362	.56	L'	.020	-5.01			35.0	-93	117
-11.1A	1000	.977		101	-10.45	.661	350	55	.04	L'	.018	-0.78			35.0	-208	165
-11.2	800	1.093		112	(.04)	.398	(76)	(-218)	(.04)	ε = 1.03	.017	1.03			28.0	-221	86
-11.3	650	1.212		124	(.05)	.454	(66)	(-229)	(.03)	L'	.016	1.06			22.2	-231	101

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

TABLE II (CONT.)

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	Coolant-Side QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	Gas-Side QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	T_c °F	V ft/sec	M -
7A-1.1	-1.07	12.41	585	12.18	575	348	22.39	673	22.43	662	1686	33	157	.05
-1.2	-1.07	8.91	681	8.76	671	453	18.05	749	18.08	740	1366	111	133	.06
-1.3	-1.07	5.87	654	5.78	644	402	15.09	707	15.12	697	1139	17	80	.02
-2.1	-1.07	9.16	685	9.02	676	462	18.43	756	18.47	746	1379	27	115	.04
-2.2	-1.29	7.76	749	7.68	742	592	14.30	805	14.32	798	1100	112	121	.05
-3.1	-1.07	14.34	688	14.14	680	495	23.06	784	23.11	774	1567	37	172	.05
-3.1A	-1.07	14.34	688	14.14	680	495	23.06	784	23.11	774	1668	37	172	.05
-3.2	-1.07	8.28	750	8.19	742	584	15.57	811	15.60	803	1116	20	109	.03
-3.2A	-1.29	8.40	799	8.33	792	657	14.57	858	14.59	851	1107	27	110	.04
-3.3	-1.29	6.34	799	6.29	793	679	11.53	844	11.55	839	856	29	92	.03
-4.1	-1.29	17.93	749	17.81	745	634	22.38	852	22.40	847	1514	106	245	.10
-10.1	-1.07	12.02	659	11.87	649	445	22.08	746	22.12	735	1577	-204	164	.03
-11.1	-1.07	13.69	652	13.51	642	443	23.24	746	23.28	735	1682	-75	145	.03
-11.1A	-1.29	15.47	751	15.37	745	617	21.52	845	21.55	839	1440	-192	201	.04
-11.2	(1.03)	(10.62)	(750)	(10.56)	(745)	(655)	(15.40)	(817)	(15.42)	(811)	(1121)	(-218)	(217)	(.04)
-11.3	(1.06)	(7.45)	(800)	(7.42)	(797)	(733)	(10.79)	(847)	(10.80)	(843)	(875)	(-229)	(203)	(.03)

( ) Solution did not converge. Data in parentheses are for maximum coolant-side heat flux at the area ratio shown.

TABLE III

PROPANE AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc Psia	P_{in}/P_c -	P_{in} psia	T_{in}^* °F	Carbon Factor -	T_{coke} °F	Corre-lation -	ε -	Engine Basis	Channel Design	Computer Run Ident.
7B-1.1	10K	300	1.8	540	203	0.42	800	Hines	6:1	OMS	C	7B/2-19/2
-1.2		200		360	165							7B/2-19/2
-1.3		100		180	110							7B/2-19/1
-2.1		400	1.3	520	200							7B/2-19/3
-2.2		300		390	171							7B/2-19/3
-2.3		200		260	135							7B/2-19/3
-2.4		100		130	82							7B/2-19/3
-3.1	6K	300	1.8	540	203							7B/2-19/4
-3.2		200		360	165							7B/2-19/4
-3.3		100		180	110							7B/2-19/4
-4.1		500	1.3	650	260							7B/2-20/1
-4.2		400		520	200							7B/2-19/4
-4.3		300		390	171							7B/2-19/4
-4.4		200		260	135							7B/2-19/4
-4.5		100		130	82							7B/2-19/4
-5.1	2K	400		520	200					RCS		7B/2-20/1
-5.2		100		130	82							7B/2-20/1
-6.1	1K	400		520	200							7B/2-20/1
-6.2		100		130	82							7B/2-20/1
-7.1	6K	300	1.8	540	203					OMS		7B/3-12/1 (1),(5)
-7.2												7B/3-12/2 (2),(5)
-7.3												7B/3-12/2 (4),(5)
-8.1												7B/3-13/1 (1)
-8.2												7B/3-13/1 (3)

NOTES: $^*T_{in} = T_{sat} + 10°R$
(1) 50% of Coolant in Bypass
(2) 35% of Coolant in Bypass
(3) 25% of Coolant in Bypass
(4) 20% of Coolant in Bypass
(5) Hot-Gas Wall 0.250 in. thick (0.025 in. nominal)

TABLE III (CONT.)

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ (lbm/sec)	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Location	Channel Min. Depth in.	Channel Loca. ε	Design Limit Type -	Design Limit Loca. -	Attach ε	T @ Throat °F	V @ Throat ft/sec
7B-1.1	300	2.303	6.85	98	-10.91	11.7	118	320	.16	ε = -1.71	.187	-2.65	Coking	TML2	6:1	210	99
-1.2	200	2.821		119	-10.62	7.1	124	289	.28	ε = -1.29	.207	-3.30				190	140
-1.3	100	3.989		168	-10.92	6.7	127	237	.30	ε = -1.29	.280	Throat				144	218
-2.1	400	1.995		85	-10.49	34	130	330	.29	ε = -1.71	.095	-2.65				217	151
-2.2	300	2.303		98	-10.91	18	137	308	.24	ε = -1.71	.138	-2.65				194	154
-2.3	200	2.821		119	-10.62	10	136	271	.29	ε = -1.29	.206	Throat				164	205
-2.4	100	3.989		158	-10.92	9	135	216	.44	ε = -1.29	.280	Throat				118	314
-3.1	300	1.784	4.11	76	-11.40	17	161	364	.16	ε = -1.71	.097	-2.49				220	85
-3.2	200	2.185		93	-10.75	8	159	323	.15	ε = -1.29	.134	-2.65				191	107
-3.3	100	3.090		130	-11.04	4	152	262	.22	ε = -1.29	.277	-3.00				143	164
-4.1	500	1.382		59	-10.92	130	190	450	.39	L'	.053	-2.65				282	213
-4.2	400	1.524		66	-11.12	49	179	379	.28	ε = -1.71	.073	-2.65				218	144
-4.3	300	1.784		76	-11.40	27	183	354	.24	ε = -1.71	.093	-2.65				195	134
-4.4	200	2.185		93	-10.75	12	172	307	.22	ε = -1.29	.133	-2.65				165	155
-4.5	100	3.090		130	-11.04	5	161	404	.31	ε = -1.29	.280	Throat				118	230
-5.1	400	.892	1.37	38	(-9.52)	(299)	(282)	(382)	(.94)	(ε= -3.30)	(.026)	-3.30				221	130
-5.2	100	1.784		76	-11.40	8	228	310	.22	ε = -2.65	.096	-2.65				102	121
-6.1	400	.631	.68	27	(6.05)	(250)	(251)	(451)	(.78)		(.019)					214	50
-6.2	100	1.262		54	10.78	21	316	398	.36	L'	.049	L'				106	85
-7.1	300	1.784	2.05	85	~Throat	(73)	(36)	(239)	(.56)	~Throat	(.032)		Conv. Failure	ε= 1.06		-	-
-7.2			2.67		~Throat	(81)	(26)	(229)	(.59)	~Throat	(.038)			ε= 1.06		-	-
-7.3			3.29		~Throat	(93)	(20)	(223)	(.64)	~Throat	(.044)			ε= 1.06		-	-
-8.1			2.05	76	-11.40	113	331	534	.39	L'	.024		Coking	TML2		242	77
-8.2			3.08		-11.40	32	219	422	.20	L'	.059					227	77

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

TABLE III (CONT.)

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QA02 Btu/in^2-sec	TWG2 °F	QA03 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
7B-1.1	-1.07	3.84	628	3.67	610	331	7.60	657	7.63	638	532	224	106	.16
-1.2	-1.07	2.39	554	2.29	540	321	5.36	574	5.37	559	351	197	144	.20
-1.3	-1.07	1.12	426	1.08	417	284	2.94	436	2.95	426	169	153	227	.29
-2.1	-1.07	5.98	626	5.70	607	341	9.83	666	9.86	646	500	222	184	.27
-2.2	-1.07	3.78	625	3.61	606	326	7.60	654	7.63	634	378	200	168	.24
-2.3	-1.07	2.34	545	2.25	530	308	5.37	565	5.38	549	247	172	212	.28
-2.4	-1.07	1.10	411	1.07	402	268	2.95	422	2.96	412	114	128	333	.42
-3.1	-1.07	4.09	671	3.92	652	388	7.93	701	7.96	681	534	225	100	.15
-3.2	-1.07	2.31	634	2.22	618	378	5.55	654	5.57	637	355	198	110	.15
-3.3	-1.07	1.03	470	1.00	461	326	2.88	480	2.89	470	174	152	169	.22
-4.1	-1.07	9.04	705	8.69	689	461	12.42	760	12.46	742	612	288	257	.34
-4.2	-1.07	6.38	670	6.11	651	400	10.25	712	10.29	692	503	224	175	.26
-4.3	-1.07	4.03	672	3.87	653	390	7.93	703	7.96	683	380	201	158	.22
-4.4	-1.07	2.27	629	2.19	613	370	5.56	649	5.58	632	253	174	160	.22
-4.5	-1.07	1.02	457	.99	448	312	2.89	467	2.90	458	122	128	239	.31
-5.1	-1.29	7.80	800	7.61	786	603	8.93	847	10.56	832	503	234	172	.25
-5.2	-2.65	.84	799	.80	772	668	1.85	806	1.86	778	126	141	172	.22
-6.1	-3.30	4.74	800	4.40	775	60[illegible]	5.64	836	5.67	809	270	451	781	.78
-6.2	-2.65	1.06	800	1.02	775	682	1.98	808	1.99	782	124	150	221	.28
-7.1	(1.06)	(5.35)	(437)	(5.35)	(437)	(395)	(5.53)	(712)	(5.53)	(712)	(467)	(239)	(403)	(.56)
-7.2	(1.06)	(5.20)	(412)	(5.20)	(411)	(358)	(5.56)	(683)	(5.56)	(683)	(459)	(229)	(422)	(.59)
-7.3	(1.06)	(5.15)	(394)	(5.14)	(394)	(335)	(5.58)	(665)	(5.58)	(664)	(447)	(223)	(454)	(.64)
-8.1	-1.29	4.94	800	4.83	788	647	7.30	831	7.32	818	530	267	133	.18
-8.2	-1.07	4.02	737	3.87	718	476	7.83	767	7.86	748	535	234	93	.14

TABLE IV

PROPANE AT SUBCRITICAL PRESSURES WITH NUCLEATE BOILING
PART A. ANALYSIS INPUT

Case Code	F lbF	P_c psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{coke} °F	Correlation (F.C.)	ε -	Engine Basis	Channel Design	BOSF -	Boiling Coeff. Btu/in^2-sec °F	Wall Thick. in.	Computer Run Ident.
7C-1.1	10K	300	1.8	540	-295	0.42	800	Hines	Rad.Attach.	OMS	D	1.6	2.0	.025	7C/2-28/2
-1.2													.05		7C/2-28/4
-1.3					-44										7C/2-29/1
-1.4					-295						A	1.0			7C/2-29/3
-1.5														.250	7C/3-3/1
-1.6											C				7C/3-3/1
-1.7											D				7C/3-3/1
-2.1		100		180							C	1.6	2.0	.025	7C/2-27/2
-2.2															7C/2-29/2
-3.1	6K	300		540							A				7C/2-27/1
-3.2															7C/2-27/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	ϵ_f (last calc.)	ΔP/Pc to ϵ_f	ΔT to ϵ_f °F	T @ ϵ_f °F	M_{max} -	M_{max} Loc.	Channel Min Depth in.	Channel Loc. ε	Design Type -	Limit Loc.	V ΔT_{sub} @ ϵ_f f °F/sec	Rad. Attach ϵ_A	Max. Coolant Flux Btu/in^2-sec	Max. Coolant-Side Wall Temp. °F
7C-1.1	2.303	6.85	91	1.16	76	42	207	.01	ε=1.16	.039	3.77	BOSF	ϵ_f	37,000	9.25	3.13	196
-1.2				1.09	177	44	209	.03	ε=1.09	.030	1.09			70,008		5.56	280
-1.3				2.21	135	28	444	.04	ε=2.21	.018	2.21			25,900		2.27	196
-1.4			234	-3.30	310(1)	189(1)	354(1)	.02	(1)	.015	(1)		(1)	20,100		5.77	314
-1.5			257	-3.30	386(2)	147(2)	312(2)	.02	(2)	.016	(2)		(2)	20,600		6.33	324
-1.6			107	1.29	328	65	230	.03	ε=1.29	.017	1.29		ϵ_f	71,600		7.70	339
-1.7			100	-1.05	298	55	220	.03	ε=-1.05	.027	-1.05			74,800		8.89	348
-2.1	3.989		168	1.06	41	13	178	.01	ε=1.06	.023	1.06			28,460	2.14	2.38	83
-2.2			158	1.03	102.5	14	179	.02	ε=1.03	.026	1.03			42,600		3.58	147
-3.1	1.784	4.11	182	1.09	99	47	212	.02	ε=1.09	.018	1.09			49,700	9.89	4.08	184
-3.2				1.09	100	47	341	.02	ε=1.09	.018	1.09			49,900		4.13	184

(1) L' = -10.91 in.
(2) L = -7.75 in.
Negative values of ε refer to area ratios between throat and injector.

TABLE V

METHANE AT SUPERCRITICAL AND SUBCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	State	F lbF	Pc psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{Coke} °F	Corre-lation	ε -	Engine Basis	Channel Design	Computer Run Ident.
11A-1.1	$P > P_{crit}$	10K	1000	1.8	1800	-259	.765	1300	Lox	Rad. Attach.	OMS	A	11A/3-21/1
-1.2			700		1260								
-2.1		6K	1000		1800								11A/2-21/1
-2.2			700		1260								
-3.1		2K	800		1440						RCS		
-4.1		1K	400		720								11A/2-21/2
11B-1.1	$P < P_{crit}$	10K	400		720	-107			Hines	6:1	OMS	C	11B/2-21/1
-1.2			200		360	-151							
-2.1		6K	400		720	-107							
-2.2			200		360	-151							
-3.1		3K	300		540	-119					RCS		
-4.1		1K											11B/3-31/1
-4.2							1.0						

TABLE V (CONT.)

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Loc	Design Type -	Limit Loc. -	Rad. Attach ε	T @ Throat °F	V @ Throat ft/sec
11A-1.1	1000	1.262	5.86	129	-10.78	.283	302	43	.20	L'	.040	ε=-2.65	Cycle Life	TWL2-TBS	32.1	-162	123
-1.2	700	1.508	5.86	154	-11.07	.159	289	-30	.14	L'	.051	Barrel	Cycle Life	TWL2-TBS	22.4	-185	61
-2.1	1000	.977	3.52	101	-10.45	.464	401	-142	.27	L'	.027	ε=-2.65	Cycle Life	TWL2-TBS	34.0	-157	132
-2.2	700	1.168	3.52	120	-10.67	.324	325	66	.19	L'	.028	Barrel	Cycle Life	TWL2-TBS	24.0	-169	76
-3.1	800	.631	1.17	66	(.31)	(.149)	(118)	(-141)	(.08)	L'	.019	L'	Cycle Life	TWG3	30.5	-160	134
-4.1	400	.631	.59	66	(-.76)	(.06)	(87)	(-172)	(.03)	L'	.015	L'	Cycle Life	TWG3	11.7	-208	10
11B-1.1	400	1.995	5.86	85	-10.49	.068	243	136	.14	L'	.120	ε=-2.65	Cycle Life	TWL2-TBS	N/A	-89	110
-1.2	200	2.821	5.86	119	-10.62	.045	230	79	.17	ε=-1.29	.266	ε=-2.65	Cycle Life	TWL2-TBS	N/A	-121	150
-2.1	400	1.545	3.52	66	-11.12	.090	347	240	.17	L'	.091	Barrel	Cycle Life	TWL2-TBS	N/A	-88	96
-2.2	200	2.185	3.52	93	-10.75	.040	384	142	.13	ε=-1.29	.205	ε=-3.00	Cycle Life	TWL2-TBS	N/A	-119	117
-3.1	300	1.262	1.76	54	-10.78	.090	495	307	.17	L'	.083	ε=-2.65	Cycle Life	TWG3	N/A	-90	104
4.1	↓	.728	.59	32	-10.16	.400	737	619	~.3	L'	.027	Barrel	Cycle Life	TWG3	N/A	-98	43
4.2	↓	.728	.59	32	(7.6)	.337	732	614	~.3	L'	.027	Barrel	Cycle Life	TWG3	N/A	-90	46

TABLE V (CONT.)

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,\ max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
11A-1.1	-1.07	11.14	342	10.87	330	27	23.48	429	23.54	416	1737	-154	148	.05
-1.2	-1.07	5.45	353	5.33	340	-1	17.10	409	17.14	396	1242	-175	74	.02
-2.1	-1.07	12.82	491	12.59	479	229	24.01	583	24.07	571	1725	-148	165	.06
-2.2	-1.29	7.30	715	7.22	706	492	15.87	774	15.90	765	1228	-152	100	.04
-3.1	-1.29	15.21	908	15.15	904	808	19.10	997	19.12	993	1321	-141	201	.08
-4.1	-1.29	4.47	964	4.46	962	913	6.78	994	6.78	991	709	-191	50	.02
11B-1.1	-1.07	5.66	389	5.39	367	26	10.29	429	10.34	406	711	-82	125	.12
-1.2	1.00	2.58	200	2.47	186	-25	5.46	220	5.47	206	353	-121	150	.15
-2.1	-1.07	5.99	437	5.73	414	92	10.73	479	10.78	455	712	-60	122	.12
-2.2	1.00	2.47	277	2.37	268	27	5.66	297	5.68	281	355	-119	117	.11
-3.1	-1.07	4.16	579	4.02	557	268	8.66	611	8.70	568	535	-67	128	.11
4.1	-3.3	3.32	973	3.08	948	796	4.23	1000	4.25	974	420	619	900	~.3
4.2	-3.3	3.32	973	3.08	948	796	4.23	1000	4.25	974	439	614	830	[illegible]

TABLE VI

RP-1 AT SUPERCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	State	F lbF	P psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{coke} °F	Corre- lation	Engine Basis	Channel Design	Computer Run Ident.
6A-1.1	$P > P_{crit}$	10K	1000	1.8	1800	70	0.25	550	Hines	OMS	A	6A/2-26/1
-1.2			500		900							6A/2-27/1
-2.1		6K	1000		1800							
-2.2			500		900							
-3.1		10K	1000		1800		1.0					
-4.1		10K	315		567	60	0.25	550			A'	5A.4-2/1
-4.2			315		567			800				6A/4-2/2
6C-1.1	$P < P_{crit}$	10K	100		180			550			A	5C/4-9/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels -	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	V_{max} ft/sec	V_{max} Loc.	Channel Min. Depth in.	Loc.	Design Type -	Limit Loc. -	Rad Attach. ε	T @ Throat °F	V @ Throat ft/sec
6A-1.1	1.262	7.30	129	(Throat)	(.707)	(37)	(107)	(335)	Throat	(.015)	Throat	Coking	TWL2	31.0	107	335
-1.2	1.784	7.30	182	-10.44	1.78	110	180	197	ε=-.9	.017	ε=-1.71			15.3	98	157
-2.1	.977	4.38	101	(ε=1.09)	(.271)	(43)	(113)	(191)	ε=1.09	(.019)	ε=1.09			33.3	-	-
-2.2	1.382	4.38	141	(Throat)	.440	(30)	(100)	(185)	Throat	(.015)	Throat			16.2	100	185
-3.1	1.262	7.30	129	(ε=-1.15)	(1.090)	(158)	(228)	(361)	ε=-1.15	(.015)	ε=-1.07			31.0	209	293
-4.1	2.248	7.30	114	(-.80)	1.63	(30)	(91)	(232)	ε=-1.15	.032	ε=-1.11			9.33	84	168
-4.2	2.248	7.30	114	-10.83	.260	98	158	82	ε=-1.80	.035	ε=-2.20			9.33	34	32
6C-1.1		No Design Available														

TABLE VI (CONT.)

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $0/A_{c,max.}$	QAI2 Btu/in²-sec	TWL2 °F	QAIC Btu/in²-sec	TWLC °F	TBS °F	QA02 Btu/in²-sec	TWS2 °F	QA03 Btu/in²-sec	TWS3 °F	P psia	Tc °F	V ft/sec
6A-1.1	(1.00)	(16.39)	(550)	(16.25)	(647)	(460)	(20.27)	(643)	(20.28)	(639)	(1093)	(107)	(336)
-1.2	-1.29	8.40	550	8.35	548	493	10.89	599	10.90	596	445	106	197
-2.1	(1.09)	(9.59)	(550)	(9.49)	(546)	(471)	(13.07)	(607)	(13.08)	(613)	(1529)	(113)	(191)
-2.2	(1.00)	(8.83)	(552)	(8.78)	(548)	(495)	(11.52)	(603)	(11.52)	(600)	(680)	(130)	(185)
-3.1	(-1.15)	(17.98)	(552)	(17.83)	(549)	(469)	(20.83)	(650)	(20.84)	(646)	(710)	(228)	(361)
4.1	Throat	(9.4)	(549)	(9.4)	(550)	(520)	(7.4)	(591)	(7.44)	(593)	(<140)	(90)	(230)
4.2	-1.8	5.02	800	5.00	797	730	5.84	828	5.84	824	505	99	82
6C-1.1	No Design Available												

* Case 6A - Analyses at supercritical pressures

Case 6C - Analyses at subcritical pressures with forced convection and nucleate boiling

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by notation in L' column.

TABLE VII

AMMONIA AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES (in Zr-Cu)

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Correlation	ε -	Engine Basis	Channel Design	Computer Run Ident
128-1.1	10K	900	1.8	1620	280	Hines	6.0	OMS	C	128/4-9/1
-2.1	6K	900	1.8	1620	280	Hines	6.0	OMS	C	128/4-10/1
-3.1	1K	400	1.8	720	260	Hines	6.0	RCS	C	128/4-10/1
-4.1	1K	100	1.8	180	240	Hines	6.0	RCS	C	128/4-10/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius	$\dot{W}_c$ lbm/sec	No. of Channels	L' in	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loc.	Design Limit Type	Design Limit Loc.	T @ Throat °F	V @ Throat ft/sec
128-1.1	1.330	12.00	57	-10.86	.200	80	360	.40	ε=-0.66	.100	Inj.	Cycle Life	TWG2-TBS	285	475
-2.1	1.030	7.20	44	-10.51	.331	112	392	.40	ε=-0.51	.064	Inj.			285	492
-3.1	.631	1.20	27	(-8.62)	.520	(393)	(653)	.55	L'	.041	Inj.		TWG2	282	467
-4.1	1.262	1.20	54	-10.78	.080	334	(574)	.21	L'	.142	Inj.		TWG2	254	214

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
128-1.1	-1.07	15.74	538	15.14	528	283	17.96	623	18.01	612	1562	274	303	.26
-2.1	-1.07	16.67	541	16.67	531	290	18.79	630	18.84	619	1571	274	290	.25
-3.1	-1.07	6.27	801	6.02	781	570	9.68	844	10.37	823	665	286	529	.34
-4.1	-1.07	.61	807	.60	795	546	2.99	816	3.00	804	177	276	241	.15

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

TABLE VIII

AMMONIA AT SUBCRITICAL PRESSURES WITH NUCLEATE BOILING (in Zr-Cu)

PART A. ANALYSIS INPUT

Case Code	F lbF	P_c psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Correlation (F.C.)	ε -	Engine Basis	Channel Design	BOSF -	Boiling Coeff. Btu/in^2-sec-°F	Computer Run Ident.
12C-1.1	10K	300	1.8	540	-28	Hines	5.89	OMS	A	1.0	0.05	12C/4-2/1
-2.1	6K	800	1.8	1440	↓	↓	18.98	OMS	A	↓	↓	12C/4-2/2
-3.1	2K	800	1.8	1440			21.79	RCS	A"			12C/4-14/1
-3.2	↓	500	1.8	900			12.80	RCS	A"			12C/4-14/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in	$\dot{W}_c$ lbm/sec	No. of Channels	ϵ_f (last calc.)	ΔP/Pc @ ϵ_f	ΔT to ϵ_f °F	T @ ϵ_f °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loc ε	Design Limit Type -	Design Limit Loc	T @ Throat °F
12C-1.1	2.303	12.00	234	-3.30	.015	136	109	.005	Inj.	.145	Inj.	BOSF	Ea.Sta.	-10
-2.1	1.093	7.20	112	-1.37	.025	50	22	.010	ε=-1.37	.127	Throat	BOSF	Ea.Sta.	5
-3.1	.631	2.40	66	-2.37	.029	69	41	.012	ε=-1.07	.049	ε=-2.37	BOSF	Ea.Sta.	10
-3.2	.798	2.40	83	-1.01	.018	38	11	.008	ε=-1.01	.076	ε=-1.01	BOSF	Ea.Sta.	5

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °R	QAIC Btu/in^2-sec	TWLC °R	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	T_c °F	V ft/sec	M -
12C-1.1	-1.07	5.80	110	5.73	109	-1.4	7.42	143	7.43	141	536	-6	25	.008
-2.1	1.00	11.24	231	10.95	225	18	17.31	302	17.33	295	1423	6	54	.009
-3.1	-1.07	12.71	534	12.41	528	356	19.02	614	19.05	607	1414	15	67	.012
-3.2	1.00	8.42	179	8.21	169	45	12.99	233	12.88	222	891	5	43	.007

ORIGINAL PAGE IS
OF POOR QUALITY

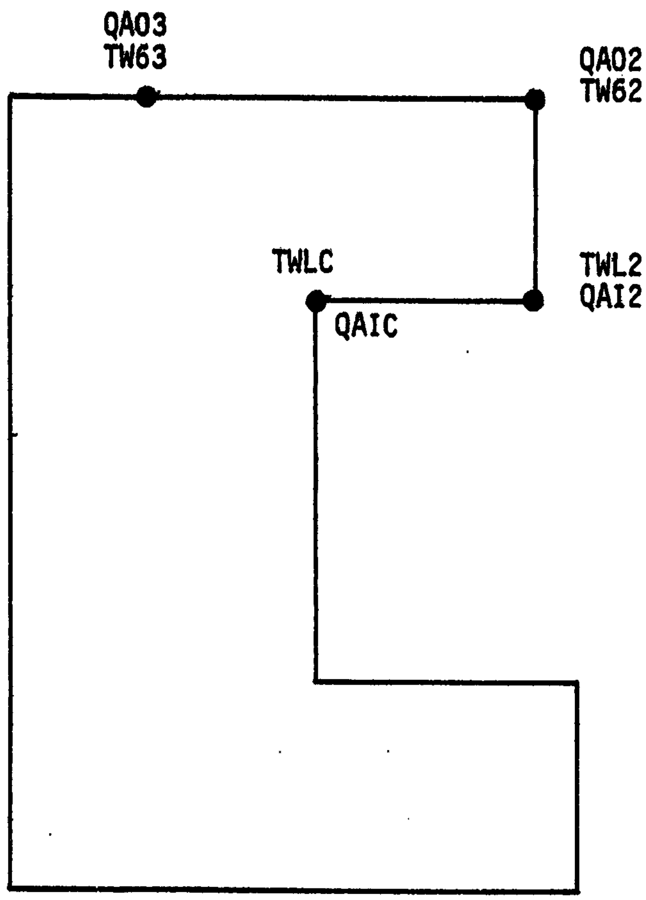


Figure 8. Nomenclature in Coolant Channel Thermal Analysis

ORIGINAL PAGE IS
OF POOR QUALITY

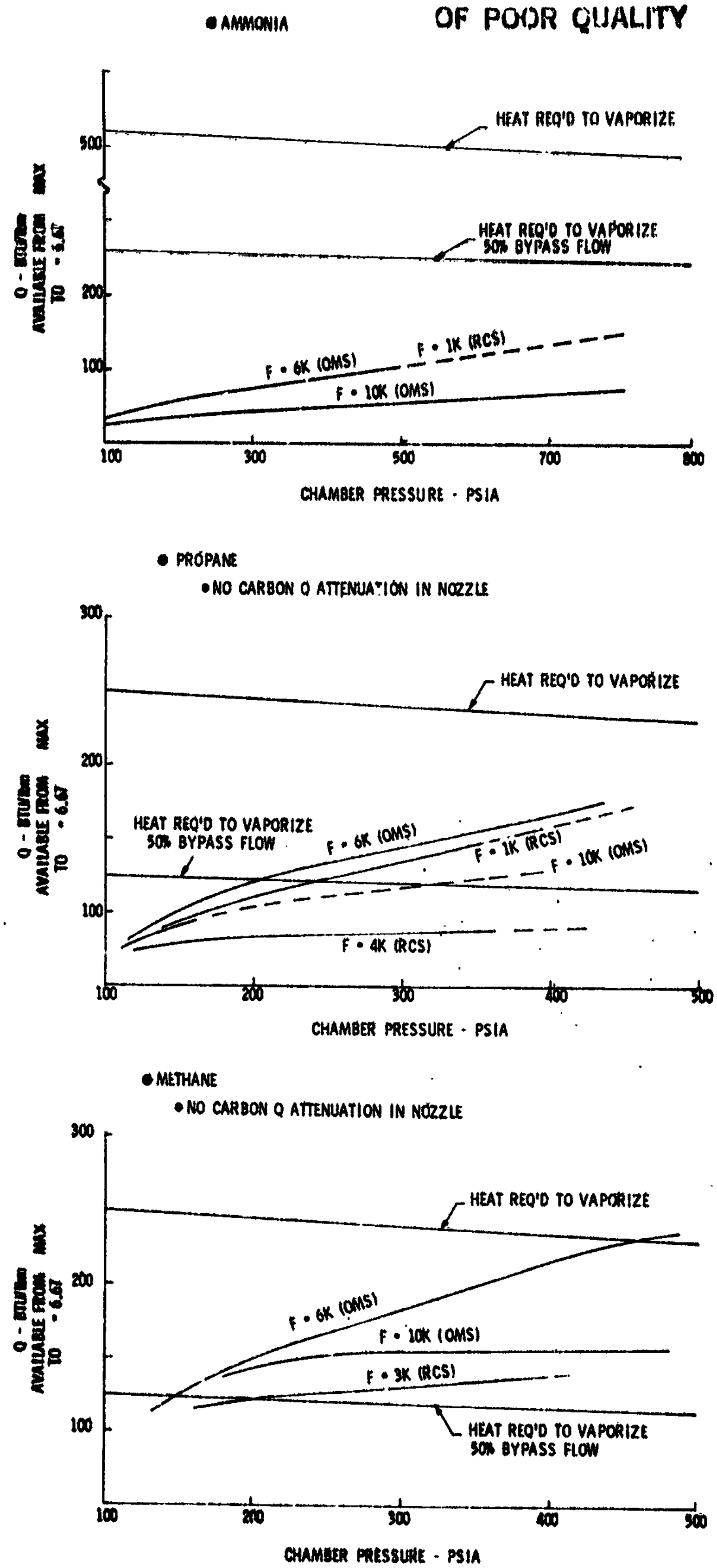


Figure 9. Heat Av^ilability Evaluations

2. Scope

Twelve individual tests were conducted. These tests exceeded 18,600 sec in duration and generated 840 individual data points. Table IX summarizes test conditions.

Forced convection heat transfer coefficients were measured over the following ranges:

Pressure:	450 to 1800 psia
Bulk Temperatures:	-250 to +250°F
Velocity:	50 to 160 ft/sec
Heat Flux:	0.2 to 10 Btu/in.^{2} sec

Nucleate boiling coefficients and critical heat fluxes were determined over the following ranges:

Pressure:	450 to 500 psia
Bulk Temperature:	-240 to - 12°F
V ΔT_{sub}:	20,000 to 40,000°F ft/sec

Coking was evaluated over the following ranges:

Pressure:	1800 psia
Bulk Temperature:	70 to 230°F
Wall Temperature:	350 to 1000°F
Velocities:	50, 150 ft/sec
Propane Grade:	Instrument (99.5%)
	Natural (96%)

3. Results and Conclusions

A correlation for forced convection was developed which grouped 95% of the data within ±24%.

Only a limited amount of nucleate boiling data were obtained. The critical heat flux values measured were significantly higher (80 to 100%) than predicted on the basis of extrapolation of published low V ΔT_{sub} data.

Coking was observed at wall temperatures as low as 500°F. Coking rates were comparable to those published (Ref. 11) for RP-1. Propane purity did not affect the temperature threshold of coking, but did affect coking rate.

TABLE IX

HEATED TUBE TEST SUMMARY

Test Number HTB6-797-	Nominal Test Conditions**				Test Objectives*
	Inlet Pressure psia	Inlet Temp °F	Inlet Vel ft/sec	Heat Flux (Max) BTU/in^2-sec	
101	1000	Ambient	50	4	SC-FC: Evaluate heat transfer coefficient
102	1000	Ambient	150	10	SC-FC: Velocity effects
103	750-1800	Ambient	100	10	SC-FC: Velocity and pressure effects
104	750-1800	-44 (NBP)	50	6	SC-FC: Bulk temperature effects
105	750-1800	-44 (NBP)	100	10	SC-FC: Bulk temperature effects
106	500	-44 (NBP)	100	7	Sub-FC: NUB: FB: Evaluate heat transfer coefficients and determine $\phi_{B.C.}$
107	1800	Ambient	50	6	SC-FC: Evaluate coking @ low velocity
108	1800	Ambient	150	10	SC-FC: Evaluate coking @ high velocity
109	500	-175	125	12	Sub-FC: NUB: FB: Bulk temperature effects
110	500	-250	100	6	Sub-FC: Bulk temperature effects
111	500	-250	100	11	Sub-FC: NUB: FB: Bulk temperature effects
112	1800	Ambient	50	6	SC-FC: Evaluate coking with instrument grade (99.5% purity) propane

*Heat Transfer Modes

Supercritical Forced Convection (SC-FC)
Subcritical Forced Convection (Sub-FC)
Nucleate Boiling (NUB)
Film Boiling (FB)

**Propane Grade

Tests: 101-111 (Natural)
Test: 112 (Instrument)

4. Test Facility

a. ALRC Heat Transfer Test System

The heat transfer test facility, shown schematically in Figure 10, consists of the following: 1) a 150 gallon 5500 psi, vacuum-jacketed, propane run tank with a high-pressure helium pressurization system; 2) a jacketed run line; 3) an enclosed, electrically heated test section; 4) 225 Kw DC power supply; and 5) all necessary controls and instrumentation.

The test section apparatus was enclosed in a 1/2 in. thick aluminum box. The test section enclosure was covered with an acrylic window and purged with dry nitrogen to maintain an inert atmosphere. During testing, the test section was monitored continuously with a closed-circuit television.

The test section was clamped into electrical connections cantilever-mounted in the test section enclosure. The upper connection was supported with flexures to permit axial movement of the heated test section tube due to thermal expansion. To ensure free axial movement, a tension force was applied to the outlet end of the test section. The inlet of the test section was maintained at ground polarity, and the outlet mixer incorporated electrical insulation to isolate the test section from downstream plumbing.

Flow control was accomplished using a 1/2 in. control valve at the test section outlet.

Bulk temperature control of the propane was provided by an LN_2-driven heat exchanger and recirculation pump system.

b. Test Sections

Electrically heated test sections were designed to give the greatest range of test conditions and data points without exceeding the strength of the tube or the capacity of the test facility.

The test section configuration, together with instrumentation locations for all tests, is shown in Figure 11. With the exception of Test 111, where the test section from the previous test was used, new test sections were used for each test.

The installation of instrumentation in the test sections is shown in Figures 12 and 13. Pressure taps were located immediately upstream and downstream of the test section and were connected to pressure transducers with 1/8 in. dia. CRES tubing. Temperature was measured at five stations spaced at even increments along the outside wall of the heated section. Two measurements,

ORIGINAL PAGE IS
OF POOR QUALITY

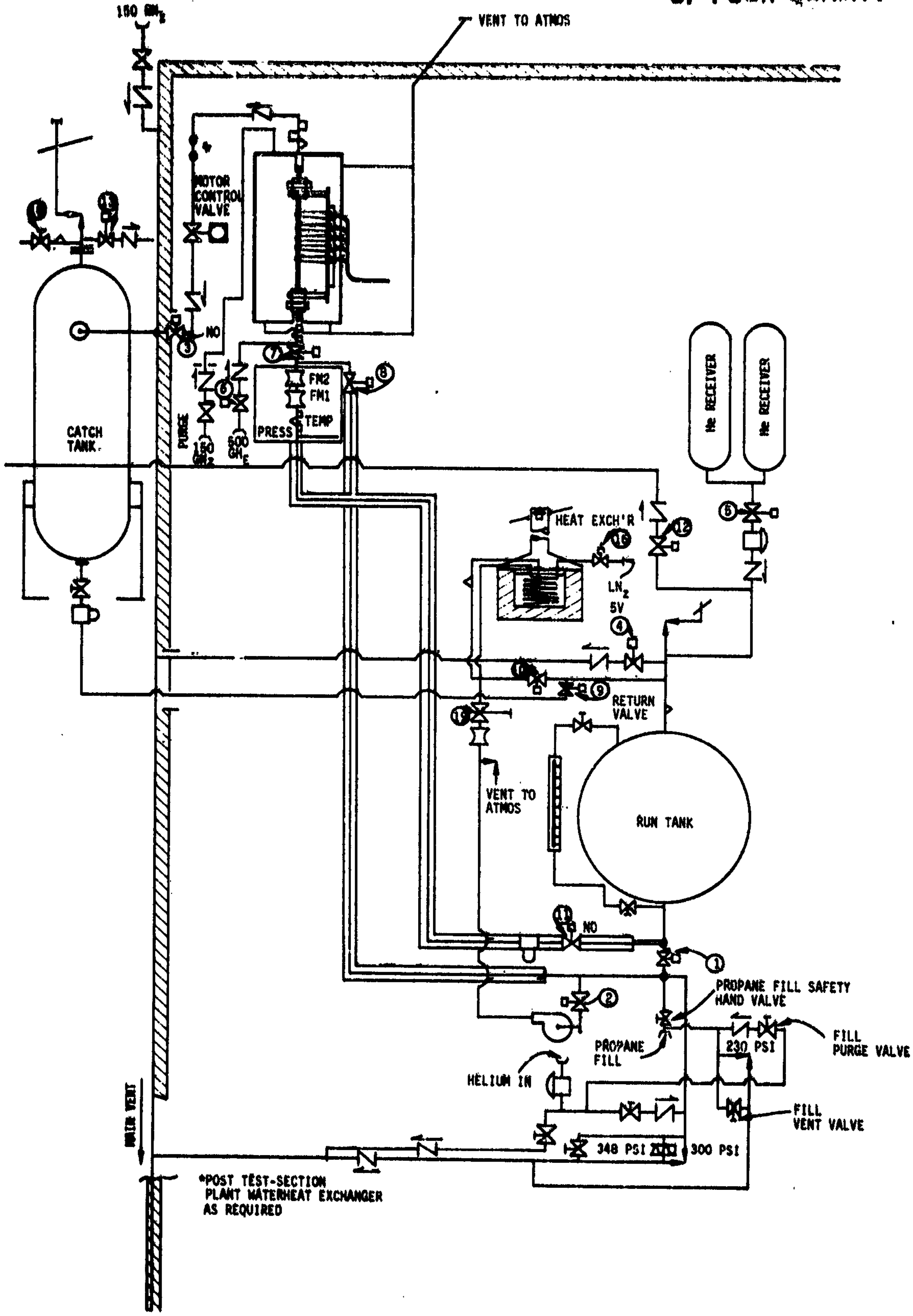
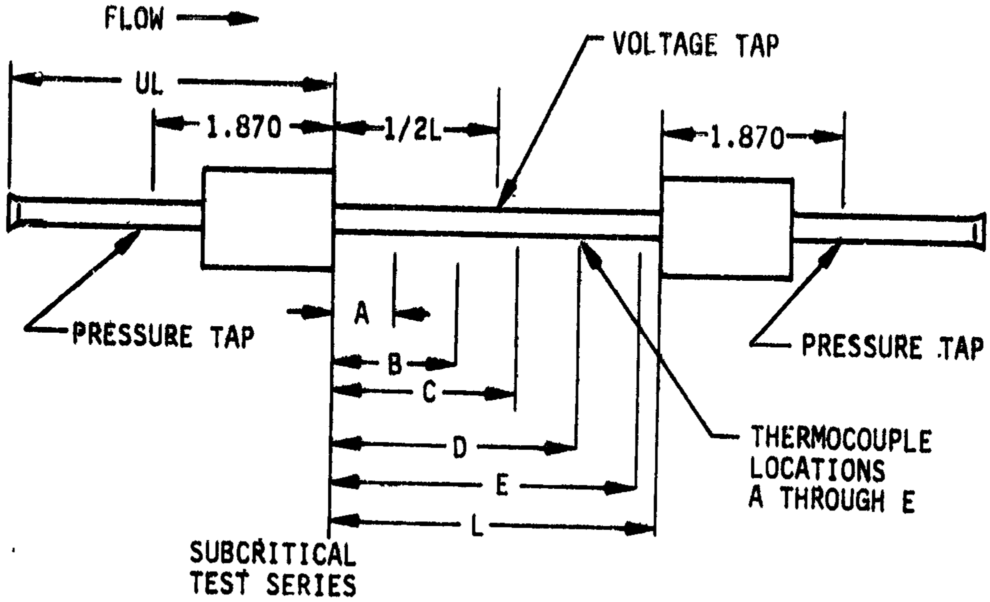


Figure 10. ALRC Heat Transfer System Schematic



TEST NO. HT86-797-	OD in.	Wall in.	UL in.	L in.	A in.	B in.	C in.	D in.	E in.	Mat'l MONEL
101	.1875	.015	4.87	10.50	2.50	4.38	6.27	8.15	10.04	K500
102	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
103	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
104	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
105	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
106	↓	↓	↓	5.00	1.57	2.36	3.14	3.93	4.71	↓
109	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
110	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
111	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
107	.125	↓	↓	5.97	1.43	2.50	3.58	4.66	5.73	↓
108	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
112	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

Figure II- Test Section Dimensions

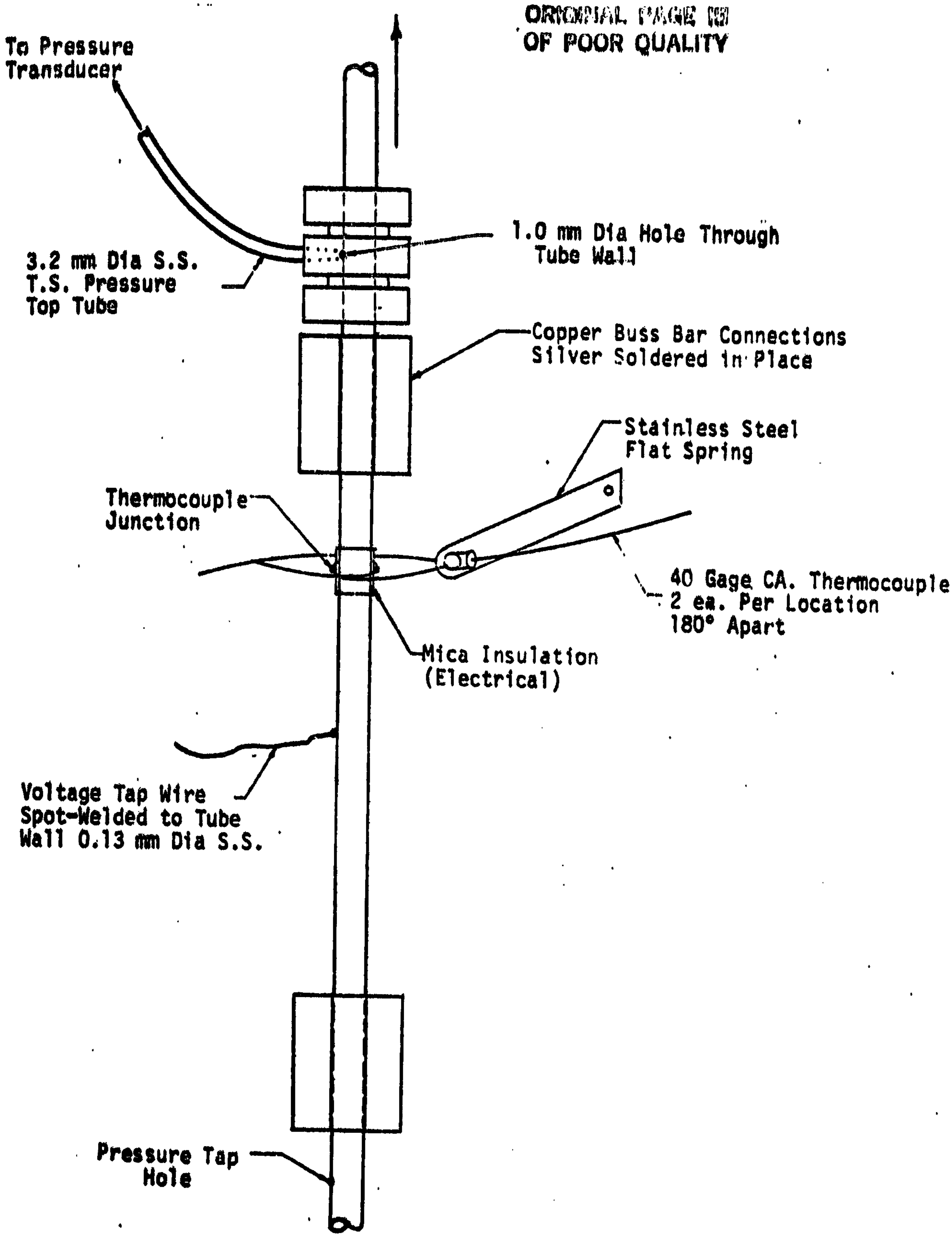


Figure 12. Heat Transfer Test Section

ORIGINAL PAGE IS
OF POOR QUALITY

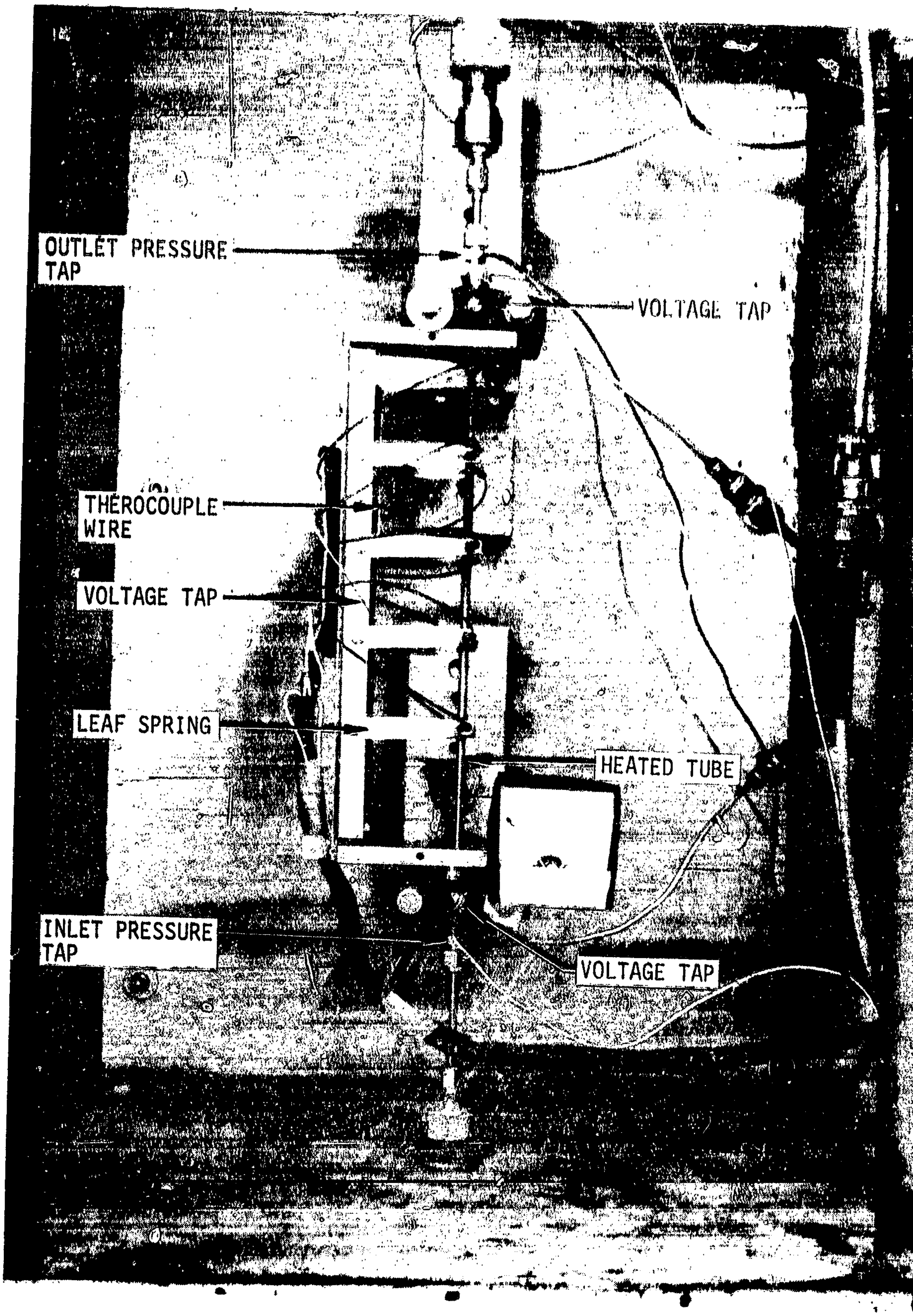


Figure 13. Test Section Installation.

located 180° apart, were taken at each station and averaged. The thermocouples were electrically insulated from the tube with a thin strip of Mica to prevent voltage from the tube interfering with thermocouple readings. To ensure good heat transfer between the tube wall and the thermocouple, the thermocouples were spring-loaded against the test section. Because the thermocouples are not directly attached to the heated tube, the measured temperature is somewhat lower than the actual wall temperature. Calibration tests for these configurations (Ref. 5) allow correlation of measured data with actual wall temperature.

c. Instrumentation

The measured parameters, together with instrument type, are listed in Table X. In addition to the standard low frequency measurements, high frequency pressure transducers, installed in both inlet and outlet mixer sections, were used to measure pressure oscillation resulting from abnormal flow or heat transfer modes.

5. <u>Heat Transfer Tests</u>

The propane heated tube test program consisted of a total of twelve individual tests. Each test was designed to cover as wide a range of test conditions and variables as fluid flow time would permit.

A detailed summary of all test conditions is presented in Table XI. At each data point, five wall temperature measurements along the length of the tube were recorded; these correspond to the thermocouple positions shown in Figure 11. Internal wall temperatures, calculated from the measured external wall temperatures, are listed in Table XII in conjunction with the calculated local coolant parameters. The data points listed in Table XI are keyed to the test section local coolant parameters, shown in Table XII, through the ID#.

Tests 101-105 were all conducted at supercritical pressure, covering a wide range of coolant bulk temperature and velocity. Typical wall temperature trends versus input heat flux for each test are plotted in Figure 14. Data trends were similar in all tests, with the heat transfer coefficient degrading at increased wall temperatures. Flow oscillations, shown shaded in the plots, often occurred at higher wall temperatures, particularly at lower pressures.

Test 106 and tests 109 through 111 were all conducted at subcritical pressure. A typical wall temperature versus heat flux for these tests is presented in Figure 15. Data trends were similar in all tests and could be separated into the various cooling regimes: forced convection at wall temperatures below the saturation temperature, forced convection with nucleate

ORIGINAL PAGE IS OF POOR QUALITY

TABLE X

PROPANE HEAT TRANSFER INSTRUMENTATION LIST

PARAMETER	SYMBOL	TRANSDUCER TYPE	RANGE	ACCURACY ±% READING	RECORDING DEVICE TAPE	VISUAL	GRAPH	DISC	MALFUNCTION DETECTION	COMMENTS
Inlet Mixer Pressure	P_{Mi}	Strain Gauge	0-2000 psi	0.25				X		Optimize
Test Section Inlet Pressure	P_{in}	" "	0-2000 psi	0.25		X	X	X		"
Test Section Outlet Pressure	P_{out}	" "	0-2000 psi	0.25		X	X	X		"
Outlet Mixer Pressure	P_{MO}	" "	0-2000 psi	0.25				X		"
Fuel Tank Pressure	P_{FT}	" "	0-2000 psi	0.5		X		X		
Flowmeter Inlet Pressure	P_{FM}	" "	0-2000 psi	0.25				X		"
High Freq. Inlet Pressure	P_{HF1}	Piezio Electric	500 p-p psi	5	X	X	X			
High Freq. Outlet Pressure	P_{HF2}	" "	500 p-p psi	5	X	X	X			
Flowmeter Temperature	T_{FM}	RTT	165-600°R	(± .5°R)				X		
Test Section Inlet Temp.	T_{IN}	RTT	"	(± .5°R)		X	X	X		
Test Section Inlet Temp.	T_{IN-R}	Thermocouple	"	(± .5°R)				X		Redundant
Test Section Wall Temp.	T_{W1-A}	"	165-1260°R	"		X	X	X		
"	T_{W1-B}	"	"	"			X	X		
"	T_{W2-A}	"	"	"		X	X	X		
"	T_{W2-B}	"	"	"			X	X		
"	T_{W3-A}	"	"	"		X	X	X		
"	T_{W3-B}	"	"	"			X	X		
"	T_{W4-A}	"	"	"		X	X	X		
"	T_{W4-B}	"	"	"			X	X		
"	T_{W5-A}	"	"	"		X	X	X		
"	T_{W5-B}	"	"	"			X	X		
Test Section Outlet Temp.	T_{out}	RTT	165-600°R			X	X	X		
Test Section Outlet Temp.	T_{out-R}	Thermocouple						X		Redundant
Test Section Voltage	V_{TS}	Voltmeter	100 VDC	.25		X	X	X		
Center Tap Voltage	V_{CT}	"	100 VDC	.25				X		
Test Section Current	I_{TS}	Shunt	3000A	.5		X	X	X	"0" after Power Up	
Test Section Current	I_{TS-R}	"	3000A	.5				X	"0" after Power Up	Redundant
Propane Flowrate	W_{F1}		.1-1.7 #/sec	.5		X	X	X	Overspin	
Propane Flowrate	W_{F2}		.1-1.7 #/sec	.5				X	Overspin	

TABLE XI

HEATED TUBE TEST CONDITION SUMMARY

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
HTB6-797-101	3-26-80	1-5	1	13	.0039	.216	1019.2	52.3	48.6	1010.6	53.3	-			
		6-10	2	101	.236	.216	1022.0	52.3	48.6	1011.6	62.6	-3.9			
		11-15	3	187	.590	.216	1022.0	52.4	48.6	1012.6	76.0	0.2			
		16-20	4	232	.656	.216	1022.0	52.5	48.6	1013.0	78.7	-0.5			
		21-25	5	322	1.34	.216	1023.1	52.6	48.6	1013.1	104.0	1.3			
		26-30	6	375	1.79	.215	1025.2	52.6	48.4	1012.7	119.7	2.4			
		31-35	7	453	2.43	.214	1025.3	52.6	48.2	1013.6	142.5	2.3			
		36-40	8	544	2.81	.214	1025.6	52.7	48.2	1014.8	155.6	1.9			
		41-45	9	586	3.11	.214	1025.9	52.7	48.2	1014.9	165.4	1.8			
		46-50	10	641	3.39	.215	1031.6	52.8	48.4	1003.1	175.8	0.6	15	15	505
		51-55	11	750	3.54	.214	1031.7	52.8	48.2	1002.8	180.4	0.4	10	6	480
		56-60	12	796	3.82	.215	1034.2	52.8	48.4	1010.7	188.5	0.3	22	8	450
102	3-31-80	61-65	1	801	4.17	.639	1034.0	60.4	145.2	926.3	144.6	-0.9			
		66-70	2	871	7.13	.629	1045.5	60.4	142.9	932.7	151.0	-0.7			
		71-75	3	921	8.76	.624	1050.7	60.5	141.8	938.8	170.0	-0.8			
		76-80	4	990	9.27	.622	1054.4	60.5	141.3	943.5	176.6	-1.8			
		81-85	5	1033	9.92	.619	1056.7	60.6	140.6	948.2	183.9	-1.5			
		86-90	6	1104	10.4	.617	1060.9	60.6	140.2	949.9	189.6	-1.7	4	4	420
103	4-1-80	91-95	1	257	3.03	.449	1840.3	62.1	100.2	1785.1	118.7	1.1			
		96-100	2	316	5.15	.445	1846.9	62.1	99.3	1788.7	157.3	0.4			
		101-105	3	371	7.19	.442	1852.4	62.1	98.6	1791.9	192.4	0.05			
		106-110	4	426	8.66	.439	1857.2	62.1	98.0	1796.3	217.3	-0.3			
		111-115	5	479	9.91	.438	1860.6	62.1	97.9	1797.1	237.3	-0.6			
		116-120	6	640	5.30	.432	1019.3	57.9	97.9	961.4	155.1	-0.06			
		121-125	7	688	6.44	.441	1018.5	57.9	99.9	958.1	172.2	-1.0			
		126-130	8	726	6.97	.439	1025.7	57.9	99.5	961.0	180.7	-1.1	7	11	460
		131-135	9	783	7.16	.440	1027.9	58.0	99.7	962.6	183.6	-1.4	20	15	450
		136-140	10	998	3.14	.442	786.3	57.0	100.7	728.5	114.9	-0.2			
		141-145	11	1052	5.24	.434	786.1	57.2	98.9	727.5	151.3	+0.2			
		146-150	12	1086	5.86	.446	785.9	57.4	101.7	730.7	158.6	0.1	26	23	460

TABLE XI (cont.)

Test Data Point Identification					Test Section Parameters								Auxiliary Parameters			
													Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
104	4-9-80	151-155	1	358	2.41	.247	1839.9	-39.6	49.4	1827.1	52.0	-0.8			
		156-160	2	418	3.60	.246	1842.8	-40.2	49.2	1827.8	94.0	-0.3			
		161-165	3	454	4.62	.246	1844.7	-40.4	49.2	1829.3	128.3	-0.8			
		166-170	4	505	5.30	.245	1846.2	-40.8	49.0	1830.4	149.5	0.2			
		171-175	5	572	5.84	.245	1849.4	-41.1	48.9	1832.4	167.0	-0.3			
		176-180	6	739	1.32	.251	1036.1	-43.6	50.5	1024.1	6.6	-1.8			
		181-185	7	804	2.56	.248	1036.1	-49.9	49.9	1023.1	50.2	0.8			
		186-190	8	898	3.75	.241	1040.2	-43.7	48.5	1030.6	93.5	1.7	7	5	>10K
		191-195	9	945	3.77	.241	1042.8	-43.4	48.5	1029.1	97.8	-0.7	7	6	>10K
		196-200	10	1014	4.49	.240	1043.0	-43.6	48.3	1032.8	121.2	-0.3	7	5	>10K
		201-205	11	1072	5.08	.255	1039.4	-43.9	51.3	1025.4	130.9	-0.5	7	6	>10K
		206-210	12	1096	5.52	.291	1035.0	-43.9	58.5	1012.4	121.7	-4.6	69	29	600
		211-215	13	1287	1.32	.245	753.7	-44.7	49.4	742.7	6.4	-1.8			
		216-220	14	1380	2.73	.241	751.9	-44.8	48.6	742.9	58.6	0.3			
		221-225	15	1418	2.89	.244	757.6	-44.8	49.2	741.7	64.1	-3.8	43	39	765
		226-230	16	1553	3.26	.241	759.4	-44.8	48.6	741.8	78.7	-1.4	35	34	705
		231-235	17	1601	3.39	.264	770.9	-44.7	53.2	729.5	90.1	-17.6	105	42	545
105	4-9-80	236-240	1	274	4.19	.493	1842.4	-47.7	97.9	1784.1	35.1	-2.9			
		241-245	2	319	6.19	.485	1848.5	-48.0	96.3	1787.1	72.6	-1.5			
		246-250	3	370	8.18	.480	1852.0	-48.1	95.3	1791.0	169.3	-1.4			
		251-255	4	407	9.55	.478	1853.9	-48.1	94.9	1791.1	133.4	-1.3			
		256-260	5	471	10.5	.465	1862.7	-47.9	92.3	1804.5	155.1	-1.9			
		261-265	6	667	4.12	.490	1044.6	-49.9	98.0	987.1	31.1	-3.1			
		266-270	7	728	6.77	.479	1048.4	-49.5	95.8	988.9	80.9	-1.2			
		271-275	8	789	8.87	.473	1051.8	-49.0	94.7	990.5	119.2	-1.4			
		276-280	9	877	10.0	.487	1070.6	-48.3	97.5	958.4	134.3	-1.8	98	80	1070/530
		281-285	10	1003	2.45	.513	805.3	-48.4	103.1	744.4	-1.0	-4.3			
		286-290	11	1042	4.38	.508	808.3	-48.2	102.1	744.0	33.6	-2.1			
		291-295	12	1077	7.06	.497	848.7	-47.9	99.8	738.9	82.5	-1.6	28	60	700
		296-300	13	1117	5.68	.498	812.0	-47.9	100.1	747.1	60.5	-3.2			

TABLE XI (cont.)

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
106	4-10-80	301-305	1	211	.512	.493	471.9	-68.5	97.5	439.5	-60.7	-44.0			
		306-310	2	273	.893	.508	462.7	-68.9	100.4	429.2	-58.1	-20.5			
		311-315	3	319	1.54	.507	463.7	-68.9	100.2	429.3	-52.2	-10.8			
		316-320	4	356	1.95	.507	465.3	-68.9	100.2	429.7	-48.7	-6.5			
		321-325	5	394	2.34	.506	466.8	-68.8	100.0	430.2	-44.9	-5.6			
		326-330	6	430	2.60	.505	466.9	-68.7	99.8	430.8	-42.3	-4.9			
		331-335	7	497	3.11	.504	467.2	-63.3	99.7	431.8	-37.0	-4.3			
		336-340	8	544	3.46	.503	468.6	-68.1	99.5	432.7	-33.7	-3.1			
		341-345	9	582	3.73	.502	469.2	-67.8	99.3	433.2	-31.0	-2.1			
		346-350	10	644	4.32	.500	470.4	-67.6	98.9	434.0	-25.1	-2.5			
		351-355	11	676	4.99	.499	471.4	-67.5	98.7	434.8	-18.8	-3.2			
		356-360	12	713	5.68 ϕ B.O.	.497	473.8	-67.2	98.4	436.3	-12.4	-3.1			
		361-365	13	751	6.13	.495	474.7	-67.1	98.0	443.8	-7.9	-3.5	40	30	910
		366-370	14	817	6.80	.492	482.1	-66.6	97.4	446.3	-.9	-4.0	40	30	910
		371-375	15	868	6.93	.489	486.7	-66.3	96.9	446.5	1.2	-4.4	42	53	600
		376-380	16	921	7.48	.489	465.4	-66.0	96.9	411.7	6.5	-4.5	64	66	480
107	4-18-80	381-385	1	0	5.77	.082	1842.9	51.3	49.7	1825.4	234.5	2.7			
		386-390	2	300	5.75	.080	1856.3	50.7	48.4	1837.7	246.3	-2.8			
		391-395	3	660	5.60	.078	1849.6	51.0	47.2	1831.4	245.9	-2.5			
		396-400	4	780	5.59	.077	1851.4	51.0	46.6	1833.6	246.2	-1.5			
		401-405	5	865	5.49	.078	1852.3	51.1	47.2	1834.8	243.1	-2.7			
		406-410	6	980	4.35	.078	1854.7	51.1	47.2	1837.2	209.8	-3.9			
		411-415	7	1280	4.35	.078	1859.7	51.2	47.2	1843.1	207.6	-2.3			
		416-420	8	1620	4.35	.079	1865.7	51.3	47.9	1849.5	207.7	-3.5			
		421-425	9	1765	4.36	.077	1865.6	51.5	46.6	1849.1	209.2	-1.67			
		426-430	10	1850	4.38	.079	1863.9	51.7	47.9	1846.9	208.8	-3.4			
		431-435	11	2040	3.75	.078	1864.6	51.7	47.2	1848.1	189.4	-2.9			
		436-440	12	2085	3.71	.077	1865.5	51.6	46.6	1849.4	188.6	-1.8			
		441-445	13	2225	3.75	.079	1871.5	51.6	47.9	1854.8	189.8	-4.4			

TABLE XI (cont.)

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
													Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	Energy Balance %	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
108	6-4-80	446-450	1	0	7.06	.256	1817.6	65.3	157.8	1645.5	147.6	-4.8			
		451-455	2	55	7.09	.260	1813.3	65.3	160.3	1634.6	147.6	-6.1			
		456-460	3	125	6.86	.261	1813.5	65.2	160.9	1634.6	145.9	-7.6			
		461-465	4	195	6.95	.261	1815.6	65.1	160.9	1636.8	146.6	-7.5			
		466-470	5	290	7.01	.261	1819.6	65.0	160.9	1639.1	147.1	-7.4			
		471-475	6	410	7.04	.262	1823.1	64.8	161.4	1641.8	147.6	-7.4			
		476-480	7	530	7.03	.262	1826.2	64.7	161.4	1645.1	147.6	-8.5			
		481-485	8	665	7.03	.262	1828.4	64.6	161.4	1647.5	147.6	-8.6			
		486-490	9	755	8.50	.261	1831.6	64.6	160.9	1647.1	162.3	-7.1			
		491-495	10	890	8.47	.261	1833.7	64.6	160.9	1649.9	161.9	-6.9			
		996-500	11	1010	8.45	.262	1836.9	64.6	161.4	1652.2	161.8	-7.4			
		501-505	12	1130	8.47	.262	1839.2	64.6	161.4	1654.7	162.0	-7.5			
		506-510	13	1250	8.48	.262	1840.4	64.6	161.4	1658.2	162.2	-7.5			
		511-515	14	1265	8.48	.262	1840.5	64.6	161.4	1658.2	162.3	-7.6			
		516-520	15	1275	8.48	.262	1840.5	64.7	161.4	1658.3	162.5	-7.7			
		521-525	16	1350	10.4	.261	1843.2	64.8	160.9	1657.8	180.7	-6.3			
		526-530	17	1375	10.3	.261	1843.7	64.9	160.9	1658.4	180.8	-6.4			
		531-535	18	1385	10.4	.261	1843.8	64.9	160.9	1658.2	180.8	-6.4			
		536-540	19	1490	10.3	.261	1846.7	65.2	160.9	1658.9	180.9	-6.3			
		541-545	20	1610	10.3	.261	1847.2	65.7	160.9	1660.6	181.3	-6.5			
		546-550	21	1735	10.3	.262	1850.4	66.2	161.4	1662.1	181.7	-6.9			
		551-555	22	1850	10.2	.262	1850.4	66.9	161.4	1663.5	181.3	-7.1			
		556-560	23	1940	10.3	.259	1856.7	67.6	160.0	1674.8	183.6	-6.7			

TABLE XI (cont.)

Test Data Point Identification					Test Section Parameters								Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
109	6-5-80	561-565	1	251	4.0	.741	543.7	-178.7	132.2	475.0	-146.3	-11.7			
		566-570	2	292	5.74	.739	545.6	-179.1	131.8	474.0	-135.3	-6.5			
		571-575	3	331	7.30	.738	546.0	-179.0	131.7	474.3	-125.0	-3.9			
		576-580	4	382	8.24	.737	548.6	-179.0	131.5	475.0	-118.1	-4.0			
		581-585	5	414	9.07	.735	549.3	-178.1	131.2	475.2	-111.9	-3.2			
		586-590	6	452	10.1	.733	551.0	-177.7	130.9	476.5	-104.3	-3.6			
		591-595	7	479	11.1	.731	553.0	-177.0	130.6	498.5	-96.8	-3.3			
		596-600	8	525	12.1	.728	559.6	-175.9	130.2	505.0	-89.2	-3.1			
		601-605	9	572	12.1	.728	564.9	-174.8	130.3	450.9	-86.4	-4.7			
		606-610	10	628	9.92	.730	552.5	-172.7	130.9	501.5	-100.7	-3.4			
		611-615	11	639	10.1	.729	553.1	-172.2	130.8	502.3	-99.4	-2.6			
		616-620	12	656	11.1	.726	556.7	-171.3	130.4	502.7	-91.1	-3.4			
		621-625	13	675	11.5	.726	556.3	-170.5	130.5	522.3	-87.3	-3.6			
110	6-26-80	626-630	1	287	3.45	.602	489.4	-242.5	102.0	461.3	-207.1	-12.0			
		631-635	2	335	4.10	.604	489.3	-243.2	102.3	460.9	-202.7	-9.5			
		636-640	3	370	4.76	.604	489.3	-243.3	102.3	460.4	-197.6	-7.3			
		641-645	4	402	5.47	.605	489.4	-243.2	102.4	459.9	-191.6	-6.2			
		646-650	5	432	6.15	.605	489.7	-243.1	102.4	459.3	-186.1	-5.0			
		651-655	6	472	6.44	.605	490.3	-242.9	102.5	459.6	-183.3	-5.0			
111	6-30-80	656-660	1	215	4.01	.597	492.0	-238.8	101.4	463.5	-197.2	-14.5			
		661-665	2	260	6.13	.596	492.5	-240.6	101.1	463.1	-182.1	-6.8			
		666-670	3	300	7.79	.594	497.1	-241.3	100.7	463.7	-168.4	-5.3			
		671-675	4	340	8.73	.593	502.2	-241.6	100.5	464.2	-160.7	-4.5			
		676-680	5	375	9.18	.592	502.1	-241.6	100.4	466.1	-156.3	-4.7	89	70	1.6K
		681-685	6	409	9.54	.591	515.8	-241.6	100.2	465.8	-152.8	-4.8	>350	157	1.6K
		686-690	7	451	10.1	.590	518.9	-241.6	100.0	468.9	-148.1	-4.6	>350	150	1.5K
		691-695	8	504	10.6	.587	520.3	-241.1	99.5	477.6	-142.1	-4.4	>350	150	1.5K
		696-700	9	525	10.6	.593	495.2	-240.8	100.6	418.8	-142.0	-5.7	>350	>300	950
		701-705	10	549	9.68	.589	527.7	-240.7	99.9	407.6	-148.8	-6.7	310	>300	950
		706-710	11	568	9.30	.589	586.2	-240.2	100.0	469.3	-151.7	-6.9	56	106	>10K
		711-715	12	598	4.00	.591	501.6	-239.4	100.4	473.1	-196.5	-17.2			

TABLE XI (cont.)

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
													Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	Energy Balance %	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
112		716-720	1	0	4.35	.091	1776.7	32.4	54.1	1752.8	162.6	5.8			
		721-725	2	355	4.32	.088	1791.3	30.8	52.2	1768.[illegible]	168.5	2.9			
		726-730	3	630	4.31	.088	1798.1	30.6	52.1	1776.5	169.8	1.5			
		731-735	4	940	4.31	.087	1804.3	30.2	51.5	1783.2	170.4	1.9			
		736-740	5	985	4.74		1804.7	30.2		1783.2	182.0	2.4			
		741-745	6	1375	4.73		1808.8	30.1		1787.8	183.0	1.4			
		746-750	7	1660	4.73		1813.3	29.8		1791.7	183.0	1.2			
		751-755	8	1870	4.73		1816.7	30.2		1796.4	183.9	0.9			
		756-760	9	1940	5.28		1817.9	30.2		1796.5	198.2	1.7			
		761.765	10	2360	5.27		1821.6	30.2		1798.9	199.0	1.8			
		766-770	11	2595	5.26		1823.1	30.2		1801.5	199.0	.9			
		771-775	12	2840	5.27		1825.1	30.7		1803.7	199.2	1.1			
		776-780	13	2915	5.74		1825.5	30.6		1803.5	211.4	1.6			
		781-785	14	3215	5.74		1828.0	30.8		1805.6	212.5	1.0			
		786-790	15	3505	5.73		1831.7	30.7		1807.0	212.5	0.8			
		791-795	16	3820	5.72		1833.8	30.8		1810.2	212.4	0.8			
		796-800	17	3920	6.20		1835.0	30.8		1810.2	223.7	1.8			
		801-805	18	4210	6.20		1835.5	31.0		1812.4	224.8	1.2			
		806-810	19	4595	6.20		1838.6	31.7		1814.4	224.9	1.4			
		811-815	20	4805	6.20		1840.4	30.9		1816.8	224.7	1.2			
		816-820	21	5115	6.19		1843.1	31.0		1818.7	224.6	1.3			
		821-825	22	5390	6.18		1845.3	31.0		1820.3	224.0	1.4			
		826-830	23	5705	6.17		1838.6	32.0		1814.1	224.9	1.1			
		831-835	24	5740	4.68		1838.4	32.1		1813.6	187.4	1.5			
		836-840	25	6005	4.68	.083	1831.7	31.9	49.2	1810.1	188.6	2.2			

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XII

HEATED TUBE STATION SUMMARY

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/ $Pr^{.4}$	Re/ 1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
101	1	67.6	1017.0	52.6	15.9	2.0	251.0	1.021	1.082	1.039	.989	2.983
	2	67.2	1016.0	52.8	27.8	2.0	252.0	1.019	1.076	1.037	.987	2.982
	3	67.4	1014.0	52.9	39.8	2.0	252.0	1.020	1.078	1.037	.988	2.982
	4	[illegible]	1013.0	53.1	51.8	2.0	252.0	1.017	1.070	1.033	.982	2.981
	5	67.5	1011.0	53.3	63.7	2.0	253.0	1.019	1.076	1.037	.988	2.980
	6	106.7	1020.0	54.8	15.9	336.0	254.0	1.082	1.306	1.139	1.038	2.974
	7	108.7	1018.0	56.6	27.8	335.0	257.0	1.083	1.310	1.140	1.041	2.966
	8	111.1	1016.0	58.5	39.8	334.0	259.0	1.085	1.314	1.141	1.044	2.958
	9	111.9	1014.0	60.3	51.8	342.0	262.0	1.084	1.307	1.138	1.046	2.950
	10	116.4	1012.0	62.2	63.7	327.0	265.0	1.091	1.329	1.147	1.051	2.941
	11	162.3	1020.0	58.6	15.9	421.0	259.0	1.207	1.763	1.305	1.096	2.960
	12	166.8	1018.0	62.2	27.8	425.0	265.0	1.215	1.774	1.306	1.102	2.941
	13	172.4	1016.0	66.5	39.8	425.0	270.0	1.226	1.801	1.312	1.105	2.931
	14	175.5	1015.0	70.7	51.8	430.0	276.0	1.230	1.799	1.309	1.105	2.920
	15	183.6	1013.0	74.9	63.7	424.0	282.0	1.252	1.862	1.324	1.114	2.909
	16	172.4	1020.0	58.7	15.9	424.0	260.0	1.266	1.878	1.330	1.110	2.957
	17	177.5	1018.0	63.4	27.8	435.0	266.0	1.250	1.891	1.340	1.117	2.938
	18	183.6	1017.0	68.1	39.8	435.0	273.0	1.265	1.928	1.347	1.121	2.927
	19	187.5	1015.0	72.8	51.8	444.0	279.0	1.271	1.930	1.345	1.121	2.915
	20	196.4	1013.0	77.0	63.7	435.0	286.0	1.304	2.020	1.357	1.135	2.901
	21	277.8	1021.0	65.8	15.9	477.0	268.0	2.624	5.184	1.845	1.416	2.935
	22	285.4	1019.0	74.0	27.8	494.0	281.0	2.753	5.256	1.863	1.422	2.911
	23	290.8	1017.0	83.2	39.8	566.0	295.0	2.926	5.492	1.899	1.429	2.885
	24	300.5	1015.0	92.5	51.8	529.0	309.0	3.025	5.407	1.884	1.432	2.864
	25	313.4	1014.0	101.7	63.7	533.0	324.0	3.350	5.345	1.878	1.437	2.840
	26	337.2	1022.0	68.6	15.9	512.0	272.0	3.919	6.670	2.091	1.484	2.925
	27	343.3	1020.0	80.6	27.8	543.0	290.0	3.987	6.307	2.030	1.432	2.890
	28	353.5	1018.0	92.7	39.8	565.0	308.0	4.114	6.016	1.975	1.418	2.863
	29	364.4	1016.0	104.7	51.8	600.0	328.0	4.105	5.687	1.918	1.40[illegible]	2.834
	30	371.1	1013.0	116.8	63.7	614.0	351.0	4.202	5.380	1.853	1.369	2.802
	31	410.4	1023.0	74.0	15.9	563.0	278.0	4.961	6.775	2.009	1.342	2.910
	32	422.7	1020.0	90.1	27.8	506.0	302.0	5.051	6.246	1.908	1.366	2.869
	33	430.6	1018.0	106.2	39.8	622.0	329.0	5.227	5.745	1.803	1.332	2.830
	34	451.1	1016.0	122.4	51.8	656.0	359.0	5.222	5.253	1.703	1.294	2.792
	35	479.7	1014.0	138.5	63.7	668.0	392.0	5.314	4.790	1.589	1.287	2.755
	36	462.1	1023.0	77.2	15.9	575.0	283.0	5.667	6.634	1.889	1.359	2.900
	37	481.0	1021.0	95.7	27.8	604.0	311.0	5.722	6.033	1.767	1.324	2.854
	38	507.5	1019.0	114.1	39.8	625.0	343.0	5.832	5.443	1.641	1.276	2.810
	39	530.6	1017.0	132.6	51.8	651.0	379.0	5.918	4.912	1.528	1.231	2.768
	40	570.2	1015.0	151.1	63.7	653.0	423.0	6.096	4.382	1.398	1.171	2.724
	41	506.3	1023.0	79.5	15.9	575.0	287.0	6.167	6.506	1.784	1.333	2.892
	42	537.9	1021.0	99.8	27.8	596.0	318.0	6.345	5.858	1.649	1.291	2.843
	43	574.1	1019.0	120.0	39.8	610.0	354.0	6.499	5.222	1.510	1.237	2.797
	44	612.9	1017.0	140.2	51.8	621.0	398.0	6.631	4.647	1.381	1.183	2.752
	45	670.2	1015.0	160.4	63.7	611.0	447.0	6.797	3.968	1.237	1.118	2.708
	46	568.2	1025.0	81.8	15.9	556.0	292.0	6.832	6.374	1.670	1.309	2.886
	47	623.5	1020.0	103.7	27.8	553.0	326.0	7.191	5.658	1.501	1.257	2.836
	48	690.6	1015.0	125.6	39.8	542.0	367.0	7.517	4.790	1.329	1.200	2.785
	49	748.9	1010.0	147.5	51.8	543.0	416.0	7.731	4.062	1.189	1.142	2.735
	50	708.9	1004.0	169.4	63.7	646.0	477.0	7.037	3.645	1.164	1.088	2.689
	51	592.7	1025.0	83.2	15.9	557.0	292.0	7.064	6.311	1.626	1.300	2.883
	52	646.7	1020.0	106.1	27.8	560.0	328.0	7.354	5.493	1.458	1.248	2.831
	53	715.5	1014.0	129.0	39.8	552.0	372.0	7.706	4.624	1.287	1.190	2.777
	54	783.0	1009.0	151.9	51.8	549.0	426.0	7.932	3.866	1.139	1.129	2.723
	55	762.1	1004.0	174.7	63.7	631.0	491.0	7.349	3.394	1.093	1.059	2.683
	56	635.4	1029.0	85.1	15.9	560.0	297.0	7.442	6.158	1.552	1.288	2.878
	57	698.7	1024.0	109.5	27.8	559.0	336.0	7.745	5.199	1.374	1.233	2.822
	58	789.7	1020.0	133.8	39.8	539.0	384.0	8.220	4.288	1.189	1.175	2.764
	59	895.0	1016.0	158.2	51.8	516.0	443.0	8.792	3.475	1.022	1.106	2.712
	60	950.9	1012.0	182.5	63.7	525.0	519.0	8.939	2.853	.910	1.023	2.667

ORIGINAL PAGE IS OF POOR QUALITY

OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp	Pressure Psia	Bulk Temp °F	L/D	Nu/ $Pr^{.4}$	Re/ 1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
102	61	282.7	1008.0	73.3	15.9	1552.0	829.0	2.755	5.226	1.856	1.027	2.913
	62	293.8	989.0	83.0	27.8	1588.0	878.0	3.052	5.608	1.926	1.046	2.886
	63	302.3	970.0	92.8	39.8	1648.0	920.0	3.323	5.643	1.939	1.050	2.863
	64	313.2	950.0	102.5	51.8	1683.0	971.0	3.698	5.575	1.934	1.065	2.830
	65	317.7	931.0	112.2	63.7	1779.0	1028.0	3.846	5.483	1.912	1.059	2.818
	66	410.4	1019.0	82.0	15.9	1733.0	854.0	4.926	6.506	1.976	1.343	2.888
	67	427.6	998.0	98.2	27.8	1810.0	928.0	5.205	6.026	1.866	1.356	2.847
	68	442.5	978.0	114.5	39.8	1908.0	1018.0	5.422	5.522	1.766	1.317	2.819
	69	460.3	958.0	130.7	51.8	1994.0	1115.0	5.553	5.049	1.662	1.276	2.776
	70	483.6	938.0	147.0	63.7	2052.0	1232.0	5.720	4.569	1.556	1.221	2.785
	71	486.6	1024.0	86.6	15.9	1771.0	866.0	5.837	6.302	1.746	1.334	2.876
	72	519.9	1004.0	106.2	27.8	1811.0	960.0	6.161	5.685	1.654	1.246	2.831
	73	556.2	984.0	125.9	39.8	1866.0	1072.0	6.503	5.075	1.515	1.231	2.786
	74	598.8	964.0	145.5	51.8	1860.0	1205.0	6.774	4.489	1.377	1.169	2.745
	75	671.5	944.0	165.1	63.7	1768.0	1368.0	7.209	3.796	1.213	1.098	2.711
	76	521.1	1028.0	88.2	15.9	1739.0	871.0	6.199	6.215	1.725	1.316	2.871
	77	566.4	1008.0	109.0	27.8	1746.0	971.0	6.635	5.555	1.566	1.262	2.824
	78	618.9	988.0	129.8	39.8	1738.0	1091.0	7.035	4.906	1.469	1.203	2.777
	79	678.6	968.0	150.7	51.8	1716.0	1239.0	7.360	4.153	1.255	1.138	2.732
	80	781.8	948.0	171.5	63.7	1581.0	1421.0	7.976	3.377	1.076	1.057	2.698
	81	563.6	1031.0	89.9	15.9	1710.0	874.0	6.662	6.123	1.644	1.297	2.866
	82	623.1	1011.0	112.0	27.8	1665.0	983.0	7.148	5.490	1.468	1.239	2.836
	83	701.3	992.0	134.2	39.8	1625.0	1112.0	7.663	4.526	1.265	1.180	2.765
	84	794.9	972.0	156.3	51.8	1544.0	1275.0	8.226	3.710	1.111	1.109	2.721
	85	960.1	953.0	178.4	63.7	1380.0	1482.0	9.574	2.876	.910	1.019	2.694
	86	604.2	1034.0	91.4	15.9	1667.0	878.0	7.028	6.044	1.575	1.284	2.852
	87	682.0	1015.0	114.5	27.8	1609.0	993.0	7.591	5.111	1.378	1.225	2.809
	88	794.6	995.0	137.7	39.8	1488.0	1131.0	8.397	4.167	1.170	1.163	2.758
	89	918.3	975.0	160.9	51.8	1385.0	1306.0	9.322	3.340	.941	1.086	2.714
	90	1125.5	955.0	184.0	63.7	1195.0	1538.0	11.819	2.522	.797	.992	2.686
103	91	298.8	1827.0	75.6	15.9	1030.0	555.0	1.637	3.080	1.523	1.196	2.901
	92	311.6	1817.0	85.7	27.8	1051.0	585.0	1.703	3.123	1.519	1.206	2.861
	93	315.9	1807.0	95.9	39.8	1101.0	608.0	1.715	3.096	1.506	1.205	2.844
	94	333.5	1797.0	106.0	51.8	1086.0	633.0	1.823	3.284	1.528	1.215	2.827
	95	356.7	1788.0	116.2	63.7	1078.0	660.0	1.947	3.385	1.535	1.222	2.808
	96	443.2	1833.0	84.8	15.9	1123.0	577.0	2.772	4.821	1.684	1.260	2.864
	97	460.9	1823.0	101.9	27.8	1147.0	616.0	2.857	4.621	1.622	1.265	2.835
	98	468.9	1812.0	118.9	39.8	1235.0	660.0	2.828	4.343	1.571	1.245	2.803
	99	495.4	1802.0	136.0	51.8	1257.0	715.0	2.950	4.115	1.499	1.225	2.756
	100	523.0	1791.0	153.1	63.7	1280.0	780.0	3.089	3.877	1.427	1.202	2.698
	101	572.6	1838.0	93.1	15.9	1189.0	591.0	3.683	5.223	1.576	1.275	2.851
	102	606.4	1827.0	116.5	27.8	1221.0	647.0	3.806	4.934	1.493	1.243	2.809
	103	617.4	1816.0	139.8	39.8	1330.0	722.0	3.769	4.485	1.413	1.212	2.745
	104	660.7	1805.0	163.2	51.8	1359.0	810.0	3.865	3.993	1.295	1.177	2.670
	105	702.3	1795.0	186.6	63.7	1397.0	913.0	3.940	3.524	1.188	1.142	2.583
	106	677.7	1843.0	99.0	15.9	1202.0	600.0	4.296	5.294	1.457	1.268	2.840
	107	733.5	1832.0	126.9	27.8	1220.0	673.0	4.491	4.685	1.317	1.228	2.783
	108	767.0	1821.0	154.7	39.8	1302.0	772.0	4.485	4.073	1.206	1.189	2.695
	109	840.7	1810.0	182.6	51.8	1303.0	885.0	4.682	3.509	1.073	1.148	2.600
	110	900.2	1799.0	210.5	63.7	1332.0	1022.0	4.795	3.008	.973	1.093	2.509
	111	792.6	1846.0	103.8	15.9	1165.0	609.0	4.942	5.112	1.314	1.265	2.833
	112	877.6	1834.0	135.2	27.8	1164.0	698.0	5.283	4.407	1.157	1.222	2.759
	113	930.3	1823.0	166.7	39.8	1229.0	814.0	5.415	3.750	1.040	1.173	2.659
	114	1028.3	1811.0	198.1	51.8	1228.0	954.0	5.949	3.143	.912	1.120	2.550
	115	1107.9	1800.0	229.6	63.7	1253.0	1131.0	6.398	2.611	.817	1.053	2.435
	116	440.5	1005.0	81.0	15.9	1175.0	584.0	5.535	6.556	1.922	1.368	2.890
	117	465.3	995.0	98.5	27.8	1211.0	638.0	5.694	5.989	1.791	1.331	2.847
	118	469.9	985.0	115.9	39.8	1321.0	704.0	5.630	5.441	1.704	1.295	2.806
	119	502.4	974.0	133.3	51.8	1334.0	775.0	5.851	4.923	1.593	1.244	2.768
	120	531.2	964.0	150.8	63.7	1364.0	862.0	6.023	4.410	1.455	1.184	2.732

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
103	121	516.6	1004.0	85.1	15.9	1202.0	608.0	6.335	6.346	1.750	1.323	2.882
	122	559.3	993.0	105.6	27.8	1213.0	677.0	6.711	5.667	1.591	1.271	2.833
	123	586.5	982.0	126.1	39.8	1275.0	759.0	6.774	5.039	1.471	1.220	2.786
	124	650.3	972.0	146.6	51.8	1234.0	856.0	7.161	4.347	1.305	1.154	2.742
	125	728.2	961.0	167.1	63.7	1178.0	975.0	7.556	3.614	1.145	1.078	2.704
	126	593.9	1010.0	87.1	15.9	1114.0	611.0	7.141	6.203	1.610	1.293	2.877
	127	629.7	999.0	109.2	27.8	1156.0	687.0	7.324	5.461	1.471	1.244	2.824
	128	682.2	987.0	131.2	39.8	1165.0	776.0	7.566	4.659	1.318	1.188	2.773
	129	798.2	975.0	153.2	51.8	1064.0	887.0	8.295	3.774	1.117	1.119	2.724
	130	928.2	964.0	175.2	63.7	973.0	1020.0	9.157	3.013	.985	1.037	2.693
	131	595.6	1012.0	87.9	15.9	1144.0	615.0	7.135	6.178	1.605	1.292	2.875
	132	670.3	1001.0	110.4	27.8	1108.0	693.0	7.645	5.268	1.408	1.234	2.821
	133	743.9	989.0	133.0	39.8	1085.0	786.0	8.094	4.422	1.239	1.177	2.768
	134	888.4	977.0	155.5	51.8	974.0	901.0	9.057	3.526	1.033	1.107	2.722
	135	1018.5	966.0	178.1	63.7	902.0	1047.0	10.186	2.804	.876	1.022	2.691
	136	301.9	773.0	70.7	15.9	1066.0	581.0	5.090	7.377	2.295	1.572	2.915
	137	315.1	762.0	81.1	27.8	1088.0	616.0	5.467	7.049	2.237	1.551	2.888
	138	313.1	752.0	91.5	39.8	1184.0	651.0	5.435	6.715	2.190	1.554	2.865
	139	321.6	741.0	101.9	51.8	1232.0	690.0	5.606	6.389	2.132	1.533	2.843
	140	329.7	731.0	112.3	63.7	1285.0	734.0	5.745	6.008	2.072	1.503	2.826
	141	435.9	772.0	79.6	15.9	1185.0	599.0	7.442	6.893	1.984	1.393	2.802
	142	456.6	762.0	96.5	27.8	1232.0	656.0	7.631	6.254	1.851	1.353	2.852
	143	470.4	751.0	113.4	39.8	1307.0	723.0	7.668	5.644	1.738	1.303	2.823
	144	493.7	741.0	130.3	51.8	1353.0	800.0	7.810	5.056	1.610	1.247	2.792
	145	522.6	730.0	147.2	63.7	1381.0	892.0	7.989	4.472	1.480	1.173	2.773
	146	490.0	773.0	81.5	15.9	1163.0	622.0	8.115	6.650	1.883	1.351	2.887
	147	542.6	763.0	99.6	27.8	1131.0	685.0	8.741	5.895	1.650	1.290	2.845
	148	595.4	753.0	117.8	39.8	1108.0	763.0	9.182	5.171	1.478	1.222	2.813
	149	710.1	743.0	135.9	51.8	975.0	850.0	10.240	4.291	1.246	1.147	2.780
	150	837.9	733.0	154.1	63.7	867.0	961.0	11.291	3.478	1.049	1.069	2.764
104	151	350.5	1837.0	-17.8	15.9	368.0	186.0	2.236	6.422	2.096	1.309	3.349
	152	360.3	1835.0	-1.4	27.8	395.0	203.0	2.268	6.124	2.035	1.303	3.261
	153	340.9	1832.0	15.1	39.8	461.0	221.0	2.074	5.209	1.907	1.276	3.188
	154	350.7	1830.0	31.5	51.8	495.0	240.0	2.128	4.987	1.855	1.275	3.105
	155	359.2	1828.0	48.0	63.7	533.0	261.0	2.188	4.765	1.802	1.273	3.034
	156	507.9	1839.0	-8.2	15.9	405.0	195.0	3.570	8.304	2.086	1.365	3.294
	157	520.4	1837.0	15.6	27.8	447.0	221.0	3.596	7.417	1.954	1.345	3.177
	158	494.3	1834.0	39.9	39.8	534.0	250.0	3.286	6.430	1.862	1.322	3.068
	159	507.7	1831.0	64.0	51.8	588.0	281.0	3.309	5.774	1.746	1.306	2.965
	160	524.9	1828.0	88.1	63.7	648.0	323.0	3.356	5.110	1.621	1.280	2.858
	161	634.6	1841.0	-.1	15.9	433.0	203.0	4.556	8.803	1.932	1.371	3.255
	162	655.2	1838.0	30.2	27.8	483.0	238.0	4.538	7.512	1.759	1.343	3.110
	163	621.8	1836.0	60.6	39.8	589.0	276.0	4.280	6.510	1.685	1.314	2.981
	164	650.1	1833.0	91.0	51.8	653.0	326.0	4.201	5.486	1.513	1.277	2.854
	165	683.1	1830.0	121.3	63.7	693.0	368.0	4.217	4.843	1.391	1.236	2.797
	166	733.6	1842.0	4.5	15.9	439.0	208.0	5.205	8.460	1.754	1.376	3.230
	167	775.5	1840.0	38.7	27.8	482.0	247.0	5.268	7.076	1.559	1.344	3.074
	168	750.7	1837.0	72.9	39.8	586.0	297.0	4.925	5.911	1.452	1.304	2.917
	169	810.6	1834.0	107.0	51.8	615.0	345.0	5.057	5.034	1.288	1.261	2.827
	170	857.3	1831.0	141.2	63.7	656.0	402.0	5.101	4.295	1.159	1.212	2.741
	171	827.1	1845.0	8.4	15.9	436.0	212.0	5.782	8.170	1.613	1.382	3.209
	172	895.3	1842.0	45.8	27.8	470.0	256.0	6.077	6.710	1.399	1.346	3.042
	173	877.3	1839.0	83.1	39.8	572.0	316.0	5.675	5.450	1.277	1.298	2.866
	174	985.1	1836.0	120.5	51.8	567.0	365.0	6.302	4.642	1.107	1.246	2.800
	175	1086.2	1833.0	157.8	63.7	582.0	436.0	7.057	3.827	.955	1.189	2.687
	176	168.8	1033.0	-31.6	15.9	368.0	185.0	1.364	2.970	1.675	1.161	3.384
	177	180.8	1031.0	-22.6	27.8	374.0	195.0	1.399	3.053	1.689	1.172	3.326
	178	165.3	1029.0	-13.6	39.8	438.0	205.0	1.326	2.625	1.582	1.142	3.278
	179	177.9	1027.0	-4.6	51.8	442.0	216.0	1.359	2.709	1.597	1.151	3.234
	180	198.1	1025.0	4.4	63.7	429.0	227.0	1.439	2.992	1.641	1.175	3.191

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr^.4	Re/1000	ρb/ρw	μb/μw	kb/kw	Cp/Cpb	Pr
104	181	365.5	1033.0	-21.5	15.9	402.0	194.0	4.496	10.786	2.633	1.484	3.320
	182	359.8	1031.0	-4.6	27.8	428.0	213.0	4.665	9.987	2.522	1.468	3.234
	183	324.4	1028.0	12.3	39.8	527.0	234.0	3.920	8.657	2.380	1.461	3.155
	184	343.7	1026.0	29.2	51.8	553.0	256.0	4.238	8.215	2.310	1.454	3.080
	185	376.0	1024.0	46.0	63.7	556.0	279.0	4.638	7.752	2.208	1.433	3.009
	186	469.0	1036.0	-11.0	15.9	466.0	200.0	6.302	10.525	2.350	1.441	3.264
	187	402.[illegible]	1036.0	13.0	27.8	506.0	228.0	6.414	9.191	2.188	1.408	3.150
	188	460.1	1034.0	38.2	39.8	620.0	260.0	5.871	8.112	2.089	1.397	3.044
	189	560.4	1033.0	62.8	51.8	646.0	296.0	6.149	7.102	1.879	1.362	2.940
	190	526.4	1031.0	87.4	63.7	725.0	336.0	6.008	6.243	1.753	1.323	2.872
	191	472.6	1040.0	-9.6	15.9	469.0	201.0	6.326	10.439	2.332	1.438	3.257
	192	497.9	1037.0	15.6	27.8	509.0	231.0	6.455	9.090	2.126	1.404	3.141
	193	478.5	1035.0	40.9	39.8	607.0	264.0	6.050	7.979	2.033	1.388	3.032
	194	457.1	1032.0	66.2	51.6	667.0	301.0	6.083	6.981	1.869	1.358	2.931
	195	479.3	1030.0	91.6	63.7	797.0	343.0	5.678	6.143	1.787	1.330	2.863
	196	6[illegible]1.4	1041.0	-4.4	15.9	453.0	206.0	7.877	9.993	2.020	1.405	3.233
	197	638.2	1039.0	25.2	27.8	492.0	242.0	8.005	8.397	1.804	1.366	3.097
	198	591.3	1037.0	54.8	39.8	615.0	282.0	7.251	7.325	1.750	1.342	2.975
	199	619.6	1035.0	84.3	51.8	675.0	330.0	7.267	6.240	1.578	1.292	2.878
	200	593.0	1033.0	113.9	63.7	819.0	384.0	6.660	5.381	1.506	1.244	2.810
	201	645.7	1036.0	-2.3	15.9	483.0	222.0	8.356	9.691	1.926	1.399	3.224
	202	760.9	1034.0	29.1	27.8	514.0	263.0	8.636	7.875	1.680	1.357	3.081
	203	669.6	1031.0	60.4	39.8	625.0	309.0	8.008	6.843	1.599	1.325	2.950
	204	686.3	1029.0	91.8	51.8	697.0	363.0	7.864	5.733	1.447	1.270	2.862
	205	670.0	1026.0	123.2	63.7	827.0	429.0	7.318	4.912	1.359	1.208	2.790
	206	666.1	1030.0	-4.5	15.9	527.0	250.0	7.999	9.998	2.015	1.405	3.233
	207	776.3	1026.0	25.2	27.8	471.0	290.0	9.486	7.648	1.587	1.360	3.096
	208	778.2	1021.0	55.0	39.8	535.0	343.0	9.219	6.501	1.466	1.324	2.974
	209	752.2	1017.0	84.7	51.8	632.0	400.0	8.635	5.705	1.392	1.276	2.882
	210	637.8	1013.0	114.4	63.7	678.0	468.0	7.216	5.277	1.439	1.232	2.809
	211	167.5	751.0	-32.5	15.9	372.0	184.0	1.401	3.155	1.720	1.177	3.373
	212	181.3	749.0	-23.4	27.8	375.0	190.0	1.461	3.350	1.750	1.199	3.312
	213	170.1	747.0	-14.2	39.8	430.0	204.0	1.383	2.900	1.649	1.167	3.266
	214	181.6	745.0	-5.0	51.8	437.0	215.0	1.432	3.032	1.667	1.182	3.222
	215	177.6	743.0	4.1	63.7	484.0	226.0	1.396	2.793	1.608	1.166	3.180
	216	358.2	750.0	-20.2	15.9	425.0	194.0	7.312	12.281	2.849	1.550	3.297
	217	340.5	748.0	-1.6	27.8	494.0	216.0	6.908	11.103	2.747	1.586	3.207
	218	291.9	747.0	16.9	39.8	660.0	239.0	5.509	9.919	2.674	1.590	3.125
	219	326.6	745.0	35.5	51.8	661.0	264.0	6.250	9.107	2.531	1.55[illegible]	3.044
	220	327.7	743.0	54.0	63.7	746.0	291.0	6.142	8.259	2.411	1.549	2.967
	221	396.0	754.0	-18.9	15.9	411.0	198.0	7.891	12.015	2.716	1.519	3.291
	222	511.0	751.0	.7	27.8	356.0	221.0	9.673	10.174	2.222	1.436	3.197
	223	568.8	748.0	20.2	39.8	367.0	246.0	10.113	8.981	2.017	1.398	3.110
	224	578.9	745.0	39.7	51.8	382.0	273.0	10.293	7.970	1.853	1.367	3.024
	225	470.8	742.0	59.3	63.7	533.0	303.0	8.514	7.585	2.006	1.400	2.946
	226	461.5	755.0	-15.4	15.9	408.0	199.0	9.037	11.405	2.471	1.478	3.273
	227	577.8	752.0	6.8	27.8	367.0	226.0	10.610	9.517	2.021	1.407	3.167
	228	614.9	749.0	28.9	39.8	384.0	255.0	10.892	8.295	1.829	1.370	3.071
	229	711.5	746.0	51.1	51.8	365.0	286.0	11.854	6.876	1.564	1.329	2.978
	230	621.4	743.0	73.2	63.7	471.0	322.0	10.437	6.530	1.617	1.309	2.909
	231	559.2	761.0	-12.6	15.9	357.0	222.0	10.474	10.690	2.174	1.436	3.258
	232	757.8	754.0	11.6	27.8	296.0	254.0	12.942	8.222	1.659	1.378	3.146
	233	743.1	746.0	35.8	39.8	337.0	289.0	12.500	7.296	1.579	1.345	3.043
	234	695.8	739.0	60.0	51.8	406.0	329.0	11.617	6.628	1.551	1.321	2.943
	235	581.2	731.0	84.1	63.7	558.0	375.0	9.878	6.279	1.643	1.301	2.882
105	236	282.8	1829.0	-28.0	15.9	734.0	351.0	1.732	4.847	1.937	1.245	3.405
	237	288.1	1818.0	-13.1	27.8	796.0	381.0	1.742	4.632	1.883	1.240	3.321
	238	306.4	1808.0	1.7	39.8	825.0	413.0	1.844	4.761	1.873	1.251	3.243
	239	318.5	1797.0	16.6	51.8	872.0	446.0	1.912	4.717	1.847	1.255	3.171
	240	339.6	1787.0	31.4	63.7	895.0	481.0	2.063	4.881	1.645	1.270	3.103

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
105	241	424.3	1834.0	-19.3	15.9	777.0	362.0	2.924	8.113	2.255	1.356	3.357
	242	430.0	1823.0	2.4	27.8	809.0	467.0	2.918	7.367	2.090	1.339	3.241
	243	457.7	1812.0	24.0	39.8	916.0	455.0	3.111	6.796	1.969	1.331	3.137
	244	478.8	1801.0	45.6	51.8	998.0	508.0	3.166	6.191	1.880	1.316	3.041
	245	499.6	1790.0	67.3	63.7	1052.9	549.0	3.505	5.684	1.739	1.305	2.946
	246	553.8	1834.0	-10.6	15.9	835.0	376.0	4.023	8.764	2.062	1.374	3.306
	247	558.2	1827.0	17.6	27.8	953.0	436.0	3.955	7.621	1.918	1.348	3.168
	248	600.0	1816.0	45.9	39.8	1013.0	503.0	4.149	6.887	1.761	1.326	3.041
	249	622.7	1805.0	74.1	51.8	1126.0	588.0	4.284	6.015	1.613	1.294	2.909
	250	662.5	1794.0	102.5	63.7	1184.0	468.0	4.295	5.274	1.486	1.263	2.835
	251	643.6	1839.0	-4.9	15.9	863.0	386.0	4.646	9.016	1.960	1.377	3.278
	252	657.0	1828.0	27.7	27.8	985.0	457.0	4.588	7.617	1.767	1.345	3.120
	253	721.9	1816.0	60.2	39.8	1032.0	536.0	4.892	6.432	1.505	1.319	2.982
	254	767.4	1805.0	92.8	51.8	1125.0	640.0	4.972	5.353	1.365	1.279	2.850
	255	833.6	1794.0	125.4	63.7	1150.0	732.0	5.166	4.634	1.219	1.233	2.786
	256	751.2	1849.0	.4	15.9	835.0	325.0	5.316	8.621	1.747	1.392	3.252
	257	783.3	1836.0	36.9	27.8	937.0	464.0	5.532	7.133	1.556	1.347	3.082
	258	874.1	1828.0	73.4	39.8	984.0	565.0	5.755	5.782	1.318	1.317	2.915
	259	953.0	1818.0	109.7	51.8	1022.0	684.0	6.152	4.862	1.154	1.261	2.822
	260	1039.9	1807.0	146.1	63.7	1056.0	765.0	6.798	4.046	1.007	1.206	2.724
	261	281.6	1031.0	-30.6	15.9	739.0	364.0	2.483	8.735	2.398	1.439	3.375
	262	283.4	1021.0	-16.1	27.8	869.0	395.0	3.026	8.391	2.330	1.448	3.291
	263	306.6	1010.0	-1.5	39.8	825.0	429.0	3.639	8.017	2.824	1.468	3.219
	264	317.9	1000.0	13.0	51.8	874.0	464.0	3.964	6.655	2.363	1.472	3.151
	265	331.3	990.0	27.5	63.7	919.0	503.0	4.211	6.309	2.397	1.468	3.045
	266	448.0	1034.0	-18.5	15.9	847.0	381.0	6.148	11.021	2.455	1.455	3.305
	267	439.3	1023.0	4.9	27.8	982.0	434.0	5.954	9.722	2.332	1.435	3.188
	268	448.6	1013.0	28.3	39.8	1041.0	492.0	5.971	8.593	2.175	1.412	3.063
	269	461.2	1002.0	51.7	51.8	1208.0	556.0	6.063	7.613	2.022	1.390	2.956
	270	-248.2	992.0	75.1	63.7	1641.0	629.0	.720	.926	.434	.841	2.068
	271	508.1	1037.0	-9.0	15.9	959.0	397.0	7.356	10.303	2.153	1.419	3.253
	272	543.9	1026.0	21.2	27.8	1126.0	467.0	7.117	8.782	1.960	1.386	3.116
	273	582.7	1015.0	51.4	39.8	1217.0	548.0	7.354	7.467	1.781	1.348	2.988
	274	660.9	1004.0	81.6	51.8	1266.0	641.0	7.717	6.252	1.558	1.293	2.889
	275	-342.4	993.0	111.8	63.7	1761.0	752.0	.636	.069	.327	.782	2.417
	276	709.0	1044.0	-4.8	15.9	854.0	418.0	8.091	9.393	1.822	1.359	3.235
	277	801.3	1024.0	27.9	27.8	876.0	499.0	9.746	7.808	1.539	1.357	3.085
	278	973.2	1004.0	60.7	39.8	823.0	593.0	11.679	5.622	1.232	1.314	2.948
	279	1085.8	983.0	93.5	51.8	832.0	702.0	13.274	4.454	1.045	1.250	2.861
	280	-393.3	963.0	126.2	63.7	1751.0	842.0	.596	.006	.288	.756	2.786
	281	136.6	791.0	-37.1	15.9	770.0	373.0	1.289	2.604	1.587	1.134	3.411
	282	136.4	780.0	-28.6	27.8	847.0	393.0	1.278	2.474	1.550	1.134	3.342
	283	148.4	769.0	-20.1	39.8	853.0	413.0	1.305	2.553	1.570	1.141	3.298
	284	161.0	758.0	-11.6	51.8	858.0	434.0	1.340	2.660	1.593	1.150	3.253
	285	-71.6	747.0	-3.1	63.7	2222.0	455.0	.929	.664	.829	.964	3.214
	286	276.6	793.0	-28.7	15.9	819.0	389.0	4.839	11.796	2.839	1.587	3.344
	287	276.1	781.0	-14.0	27.8	906.0	423.0	4.866	10.993	2.757	1.588	3.267
	288	295.7	770.0	.6	39.8	935.0	459.0	5.434	10.715	2.764	1.579	3.198
	289	310.1	758.0	15.3	51.8	982.0	498.0	5.877	10.031	2.668	1.568	3.132
	290	-145.1	747.0	30.0	63.7	1734.0	540.0	.833	.315	.619	.909	3.067
	291	389.1	823.0	-16.9	15.9	1031.0	406.0	6.934	11.681	2.689	1.509	3.284
	292	557.2	803.0	6.5	27.8	822.0	463.0	9.643	9.606	2.067	1.410	3.170
	293	654.7	783.0	29.9	39.8	781.0	526.0	10.863	8.033	1.750	1.362	3.069
	294	738.4	763.0	53.3	51.8	767.0	597.0	11.889	6.674	1.516	1.324	2.971
	295	-261.6	744.0	76.7	63.7	1671.0	678.0	.710	.023	.417	.829	2.900
	296	339.2	797.0	-22.1	15.9	917.0	395.0	6.381	12.205	2.872	1.554	3.309
	297	341.9	785.0	-2.6	27.8	1026.0	442.0	6.423	10.996	2.729	1.540	3.213
	298	366.0	773.0	16.8	39.8	1079.0	491.0	6.831	9.911	2.547	1.509	3.126
	299	384.3	762.0	36.3	51.8	1151.0	546.0	7.084	8.907	2.377	1.482	3.041
	300	-199.1	750.0	55.7	63.7	1674.0	606.0	.770	.149	.508	.869	2.961

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
106	301	-38.3	462.0	-66.1	10.0	931.0	308.0	1.029	1.187	1.080	.992	3.641
	302	-37.2	457.0	-64.8	15.0	937.0	311.0	1.029	1.185	1.080	.991	3.627
	303	-36.6	452.0	-63.6	19.9	973.0	313.0	1.028	1.176	1.077	.990	3.613
	304	[illegible]	[illegible]	-62.4	24.9	1055.0	316.0	1.026	1.164	1.072	.989	3.602
	305	[illegible]	441.0	-61.2	29.9	984.0	314.0	1.028	1.178	1.077	.988	3.591
	306	-10.4	462.0	-65.5	10.0	819.0	319.0	1.062	1.394	1.166	1.029	3.635
	307	-8.5	447.0	-63.8	15.0	821.0	322.0	1.063	1.393	1.166	1.031	3.615
	308	-7.8	442.0	-62.1	19.9	843.0	326.0	1.062	1.383	1.163	1.032	3.599
	309	-5.5	436.0	-60.4	24.9	838.0	329.0	1.064	1.387	1.165	1.035	3.585
	310	-3.3	431.0	-58.7	29.9	836.0	333.0	1.065	1.390	1.166	1.038	3.570
	311	36.1	453.0	-63.7	10.0	765.0	322.0	1.126	1.780	1.315	1.066	3.614
	312	40.3	447.0	-61.0	15.0	769.0	327.0	1.126	1.763	1.317	1.067	3.591
	313	[illegible]	442.0	-58.4	19.9	806.0	333.0	1.127	1.770	1.313	1.067	3.568
	314	[illegible]	437.0	-55.8	24.9	779.0	336.0	1.135	1.812	1.329	1.069	3.545
	315	[illegible]	431.0	-53.2	29.9	764.0	340.0	1.134	1.792	1.323	1.070	3.522
	316	[illegible]	[illegible]	-62.0	10.0	773.0	324.0	1.173	2.096	1.424	1.080	3.604
	317	67.4	449.0	-59.4	15.0	796.0	331.0	1.172	2.062	1.415	1.080	3.577
	318	72.5	443.0	-56.2	19.9	796.0	337.0	1.178	2.081	1.423	1.085	3.549
	319	79.6	437.0	-53.0	24.9	784.0	344.0	1.189	2.126	1.439	1.091	3.521
	320	86.2	432.0	-49.9	29.9	805.0	351.0	1.187	2.092	1.429	1.091	3.491
	321	[illegible]	455.0	-61.3	10.0	759.0	326.0	1.235	2.462	1.544	1.107	3.594
	322	[illegible]	[illegible]	-57.5	15.0	764.0	334.0	1.241	2.465	1.546	1.110	3.561
	323	[illegible]	444.0	-53.8	19.9	786.0	342.0	1.243	2.448	1.542	1.113	3.528
	324	111.2	438.0	-50.0	24.9	777.0	350.0	1.261	2.513	1.562	1.123	3.493
	325	113.1	432.0	-46.3	29.9	798.0	359.0	1.262	2.493	1.554	1.125	3.457
	326	115.1	456.0	-60.4	10.0	764.0	327.0	1.284	2.742	1.625	1.129	3.586
	327	119.0	450.0	-56.4	15.0	777.0	336.0	1.291	2.705	1.625	1.133	3.550
	328	122.4	444.0	-52.1	19.9	794.0	345.0	1.296	2.737	1.626	1.136	3.513
	329	[illegible]	439.0	-48.0	24.9	787.0	354.0	1.317	2.824	1.651	1.144	3.474
	330	132.5	434.0	-43.8	29.9	810.0	363.0	1.317	2.789	1.642	1.146	3.438
	331	152.5	456.0	-58.5	10.0	766.0	330.0	1.417	3.539	1.826	1.177	3.570
	332	156.5	451.0	-53.6	15.0	782.0	341.0	1.501	3.888	1.931	1.232	3.526
	333	161.0	445.0	-48.6	19.9	800.0	352.0	1.657	4.123	2.049	1.323	3.481
	334	170.4	439.0	-43.7	24.9	740.0	363.0	2.394	5.426	2.442	1.555	3.438
	335	[illegible]	434.0	-38.8	29.9	817.0	373.0	3.072	6.205	2.651	1.714	3.401
	336	176.0	457.0	-57.3	10.0	773.0	332.0	2.211	7.393	2.830	1.489	3.560
	337	181.2	452.0	-51.9	15.0	790.0	343.0	3.355	9.468	3.201	1.698	3.512
	338	186.3	446.0	-46.5	19.9	808.0	356.0	5.879	13.573	3.718	1.868	3.460
	339	195.5	440.0	-41.1	24.9	811.0	367.0	8.572	16.728	3.997	1.924	3.419
	340	200.2	435.0	-35.7	29.9	830.0	380.0	8.969	16.292	3.970	1.931	3.377
	341	195.9	458.0	-56.2	10.0	775.0	333.0	8.158	17.977	4.018	1.875	3.551
	342	201.1	452.0	-50.5	15.0	795.0	346.0	8.573	17.464	4.002	1.882	3.498
	343	205.9	447.0	-44.7	19.9	816.0	359.0	8.986	16.933	3.974	1.888	3.445
	344	216.0	441.0	-38.9	24.9	819.0	371.0	9.552	16.440	3.929	1.878	3.402
	345	221.9	435.0	-33.1	29.9	837.0	385.0	9.946	15.922	3.874	1.878	3.357
	346	237.4	459.0	-54.3	10.0	781.0	336.0	10.034	17.722	3.968	1.797	3.533
	347	242.4	453.0	-47.6	15.0	807.0	351.0	10.340	16.985	3.884	1.797	3.471
	348	247.2	448.0	-40.9	19.9	833.0	365.0	10.610	16.316	3.802	1.798	3.418
	349	257.1	442.0	-34.2	24.9	844.0	380.0	11.070	15.627	3.695	1.786	3.366
	350	260.2	436.0	-27.6	29.9	877.0	397.0	11.296	15.001	3.620	1.790	3.311
	351	269.1	460.0	-52.2	10.0	826.0	340.0	11.113	17.162	3.788	1.738	3.515
	352	271.0	454.0	-44.6	15.0	866.0	357.0	11.265	16.356	3.705	1.743	3.444
	353	271.8	448.0	-36.9	19.9	911.0	373.0	11.383	15.667	3.632	1.750	3.388
	354	280.1	443.0	-29.3	24.9	935.0	391.0	11.751	14.887	3.517	1.743	3.326
	355	292.6	437.0	-21.6	29.9	945.0	409.0	12.196	14.132	3.385	1.718	3.286
	356	309.2	462.0	-50.0	10.0	847.0	343.0	12.262	16.406	3.583	1.674	3.495
	357	325.0	456.0	-41.4	15.0	858.0	362.0	12.794	15.384	3.378	1.656	3.422
	358	339.6	450.0	-32.8	19.9	872.0	381.0	13.281	14.461	3.227	1.640	3.355
	359	363.8	444.0	-24.2	24.9	863.0	401.0	13.975	13.481	3.032	1.608	3.297
	360	378.7	438.0	-15.6	29.9	874.0	422.0	14.386	12.687	2.893	1.582	3.258

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
106	361	414.3	465.0	-48.5	10.0	714.0	345.0	14.672	14.913	2.983	1.560	3.481
	362	446.2	460.0	-39.2	15.0	705.0	365.0	15.762	13.745	2.747	1.534	3.406
	363	482.4	455.0	-29.9	19.9	691.0	386.0	16.560	12.627	2.557	1.511	3.332
	364	526.7	450.0	-20.6	24.9	668.0	458.0	17.420	11.563	2.344	1.476	3.282
	365	559.4	446.0	-11.3	29.9	661.0	431.0	18.406	10.681	2.187	1.439	3.236
	366	474.9	471.0	-46.0	10.0	710.0	349.0	16.079	13.959	2.659	1.519	3.457
	367	517.4	465.0	-35.7	15.0	695.0	370.0	17.095	12.716	2.472	1.495	3.379
	368	569.2	460.0	-25.3	19.9	672.0	394.0	18.301	11.495	2.244	1.468	3.303
	369	634.2	454.0	-15.0	24.9	636.0	418.0	19.747	10.325	2.016	1.434	3.256
	370	697.2	448.0	-4.7	29.9	609.0	444.0	21.054	9.268	1.839	1.408	3.208
	371	641.8	474.0	-45.1	10.0	551.0	348.0	19.681	12.287	2.172	1.464	3.450
	372	736.3	468.0	-34.5	15.0	511.0	371.0	21.760	10.711	1.917	1.447	3.370
	373	810.7	461.0	-23.9	19.9	490.0	395.0	23.335	9.533	1.725	1.434	3.297
	374	869.8	455.0	-13.3	24.9	480.0	420.0	24.735	8.412	1.538	1.414	3.247
	375	918.9	449.0	-2.7	29.9	476.0	446.0	26.032	7.851	1.478	1.394	3.200
	376	845.9	449.0	-43.2	10.0	463.0	353.0	25.369	10.427	1.762	1.452	3.435
	377	1067.8	440.0	-31.9	15.0	391.0	378.0	32.618	8.464	1.421	1.439	3.347
	378	1149.1	432.0	-20.5	19.9	382.0	404.0	36.511	7.553	1.297	1.421	3.286
	379	1152.7	423.0	-9.1	24.9	400.0	432.0	36.898	7.065	1.253	1.399	3.223
	380	1170.4	415.0	2.3	29.9	413.0	460.0	38.037	6.544	1.190	1.378	3.177
107	381	827.1	1839.0	95.2	15.1	379.0	163.0	5.236	5.254	1.290	1.270	2.840
	382	955.6	1836.0	128.0	26.3	360.0	210.0	5.959	4.564	1.111	1.234	2.770
	383	1015.9	1832.0	161.2	37.7	360.0	246.0	6.209	3.807	.993	1.183	2.670
	384	1040.0	1829.0	194.3	49.1	415.0	290.0	6.167	3.211	.907	1.130	2.560
	385	1170.4	1826.0	227.1	60.3	407.0	344.0	7.252	2.651	.791	1.061	2.450
	386	857.5	1852.0	97.6	15.1	365.0	180.0	5.391	5.189	1.265	1.278	0.000
	387	940.7	1849.0	132.6	26.3	367.0	208.0	5.830	4.425	1.156	1.226	0.000
	388	978.6	1845.0	168.0	37.7	408.0	247.0	5.712	3.720	1.048	1.174	0.000
	389	1012.1	1842.0	203.4	49.1	445.0	295.0	5.656	3.130	.915	1.112	0.000
	390	1127.1	1838.0	238.4	60.3	440.0	355.0	6.498	2.531	.760	1.044	0.000
	391	839.6	1845.0	97.7	15.1	364.0	176.0	5.284	5.197	1.222	1.277	0.000
	392	911.8	1842.0	132.6	26.3	375.0	203.0	5.538	4.444	1.135	1.227	0.000
	393	943.1	1839.0	167.9	37.7	414.0	241.0	5.460	3.733	1.030	1.173	0.000
	394	972.3	1835.0	203.1	49.1	456.0	287.0	5.329	3.116	.940	1.112	0.000
	395	1165.1	1832.0	238.1	60.3	411.0	346.0	6.955	2.512	.781	1.038	0.000
	396	849.0	1847.0	97.8	15.1	359.0	173.0	5.363	5.190	1.272	1.277	0.000
	397	911.1	1844.0	132.7	26.3	375.0	201.0	5.526	4.443	1.136	1.226	0.000
	398	984.0	1841.0	168.1	37.7	413.0	238.0	5.465	3.731	1.029	1.173	0.000
	399	976.8	1838.0	203.4	49.1	453.0	284.0	5.358	3.112	.937	1.112	0.000
	400	1218.4	1834.0	238.4	60.3	388.0	342.0	7.852	2.493	.756	1.039	0.000
	401	835.1	1848.0	97.1	15.1	359.0	175.0	5.251	5.213	1.287	1.277	0.000
	402	887.0	1845.0	131.5	26.3	378.0	202.0	5.352	4.480	1.159	1.228	0.000
	403	919.3	1842.0	166.2	37.7	415.0	239.0	5.288	3.778	1.051	1.175	0.000
	404	949.3	1839.0	201.0	49.1	457.0	284.0	5.160	3.163	.959	1.117	0.000
	405	1220.6	1836.0	235.4	60.3	377.0	341.0	7.954	2.536	.759	1.046	0.000
	406	665.9	1850.0	89.1	15.1	358.0	170.0	4.264	5.496	1.497	1.280	0.000
	407	689.6	1847.0	117.6	26.3	382.0	190.0	4.242	4.911	1.395	1.243	0.000
	408	703.4	1844.0	146.3	37.7	422.0	217.0	4.146	4.287	1.296	1.201	0.000
	409	717.3	1841.0	175.0	49.1	468.0	249.0	4.029	3.729	1.206	1.160	0.000
	410	942.8	1838.0	203.4	60.3	368.0	288.0	5.089	3.127	.959	1.112	0.000
	411	700.4	1856.0	88.7	15.1	337.0	170.0	4.468	5.476	1.455	1.281	0.000
	412	714.2	1853.0	116.7	26.3	365.0	189.0	4.391	4.910	1.369	1.243	0.000
	413	732.9	1850.0	145.0	37.7	399.0	216.0	4.323	4.295	1.268	1.203	0.000
	414	751.5	1847.0	173.3	49.1	436.0	247.0	4.208	3.741	1.177	1.163	0.000
	415	982.7	1844.0	201.3	60.3	346.0	286.0	5.416	3.147	.937	1.117	0.000
	416	735.6	1862.0	88.8	15.1	319.0	172.0	4.682	5.446	1.413	1.282	0.000
	417	740.1	1859.0	116.8	26.3	350.0	191.0	4.531	4.890	1.340	1.243	0.000
	418	758.2	1856.0	145.1	37.7	383.0	218.0	4.435	4.278	1.242	1.203	0.000
	419	760.9	1853.0	173.4	49.1	415.0	250.0	4.340	3.725	1.150	1.164	0.000
	420	1017.0	1850.0	201.4	60.3	332.0	288.0	5.706	3.137	.916	1.117	0.000

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr^.4	Re/1000	ρb/ρw	μb/μw	kb/kw	C̄p/Cpb	P̄r
107	421	748.9	1862.0	89.3	[illegible]	313.0	168.0	4.750	5.027	1.397	1.283	0.000
	422	754.4	1859.0	117.5	[illegible]	344.0	187.0	4.601	4.865	1.322	1.243	0.000
	423	771.5	1856.0	146.1	37.7	377.0	214.0	4.498	4.250	1.226	1.203	0.000
	424	799.5	1853.0	174.6	49.1	409.0	245.0	4.407	3.696	1.139	1.162	0.000
	425	1035.4	1850.0	202.9	60.3	327.0	283.0	5.867	3.106	.903	1.114	0.000
	426	747.8	1866.0	89.3	15.1	315.0	172.0	4.748	5.427	1.398	1.282	0.000
	427	756.5	1857.0	117.5	26.3	344.0	192.0	4.617	4.865	1.320	1.243	0.000
	428	774.4	1854.0	145.9	37.7	376.0	219.0	4.518	4.251	1.224	1.203	0.000
	429	790.5	1851.0	174.3	49.1	407.0	251.0	4.435	3.698	1.131	1.162	0.000
	430	1039.9	1844.0	202.5	60.3	326.0	289.0	5.922	3.108	.900	1.115	0.000
	431	657.2	1861.0	84.7	15.1	308.0	167.0	4.215	5.583	1.521	1.255	0.000
	432	666.0	1858.0	109.4	26.3	332.0	184.0	4.131	5.086	1.445	1.253	0.000
	433	678.4	1855.0	134.3	37.7	361.0	205.0	4.057	4.556	1.359	1.219	0.000
	434	695.0	1852.0	159.2	49.1	391.0	231.0	3.992	4.032	1.270	1.183	0.000
	435	900.8	1849.0	183.9	60.3	312.0	261.0	4.969	3.470	1.027	1.150	0.000
	436	653.7	1862.0	84.4	15.1	306.0	165.0	4.194	5.590	1.526	1.285	0.000
	437	662.5	1859.0	109.0	26.3	331.0	181.0	4.110	5.096	1.451	1.253	0.000
	438	675.0	1856.0	133.8	37.7	359.0	202.0	4.039	4.569	1.365	1.220	0.000
	439	691.1	1853.0	158.5	49.1	389.0	227.0	3.972	4.046	1.276	1.184	0.000
	440	865.6	1850.0	183.1	60.3	310.0	256.0	4.938	3.491	1.032	1.151	0.000
	441	668.8	1867.0	84.7	15.1	302.0	169.0	4.268	5.569	1.506	1.285	0.000
	442	680.0	1864.0	109.5	26.3	325.0	186.0	4.199	5.071	1.427	1.253	0.000
	443	694.0	1861.0	134.5	37.7	351.0	207.0	4.133	4.540	1.341	1.219	0.000
	444	711.2	1858.0	159.5	49.1	381.0	234.0	4.072	4.017	1.252	1.183	0.000
	445	919.1	1855.0	184.2	60.3	305.0	260.0	5.078	3.463	1.013	1.150	0.000
108	446	369.2	1776.0	85.0	15.1	1175.0	554.0	2.169	4.133	1.663	1.258	2.861
	447	404.5	1746.0	99.8	26.3	1131.0	588.0	2.448	4.378	1.662	1.263	2.835
	448	427.2	1714.0	114.7	37.7	1139.0	625.0	2.672	4.350	1.624	1.256	2.809
	449	441.7	1683.0	129.5	49.1	1165.0	671.0	2.830	4.218	1.577	1.245	2.772
	450	478.8	1652.0	144.3	60.3	1153.0	725.0	3.057	4.066	1.499	1.223	2.729
	451	366.9	1770.0	85.0	15.1	1189.0	563.0	2.159	4.108	1.660	1.258	2.850
	452	401.8	1738.0	99.6	26.3	1145.0	597.0	2.433	4.357	1.651	1.263	2.835
	453	424.2	1706.0	114.7	37.7	1154.0	636.0	2.653	4.303	1.626	1.256	2.809
	454	458.5	1674.0	129.5	49.1	1202.0	683.0	2.815	4.212	1.590	1.246	2.772
	455	475.3	1642.0	144.3	60.3	1170.0	737.0	3.054	4.069	1.504	1.224	2.729
	456	357.7	1771.0	84.5	15.1	1168.0	565.0	2.096	3.961	1.642	1.254	2.861
	457	392.0	1739.0	99.0	26.3	1142.0	598.0	2.348	4.250	1.654	1.261	2.836
	458	413.1	1706.0	113.6	37.7	1153.0	635.0	2.540	4.277	1.630	1.255	2.811
	459	427.4	1674.0	128.2	49.1	1199.0	681.0	2.689	4.158	1.586	1.246	2.775
	460	463.6	1642.0	142.7	60.3	1164.0	734.0	2.983	4.070	1.519	1.228	2.734
	461	361.0	1773.0	84.6	15.1	1188.0	565.0	2.116	4.009	1.648	1.255	2.861
	462	395.6	1741.0	99.2	26.3	1143.0	598.0	2.376	4.286	1.656	1.262	2.835
	463	417.4	1708.0	114.0	37.7	1153.0	636.0	2.579	4.300	1.628	1.255	2.810
	464	431.7	1676.0	128.7	49.1	1199.0	682.0	2.732	4.176	1.583	1.245	2.775
	465	468.1	1644.0	143.3	60.3	1166.0	736.0	3.005	4.066	1.513	1.226	2.732
	466	363.0	1776.0	84.7	15.1	1190.0	564.0	2.127	4.035	1.651	1.256	2.861
	467	398.3	1744.0	99.4	26.3	1143.0	598.0	2.396	4.311	1.658	1.262	2.835
	468	408.6	1711.0	114.2	37.7	1199.0	637.0	2.685	4.224	1.627	1.253	2.810
	469	435.0	1679.0	129.1	49.1	1199.0	683.0	2.765	4.189	1.581	1.246	2.774
	470	471.4	1646.0	143.8	60.3	1167.0	738.0	3.020	4.062	1.508	1.225	2.730
	471	365.2	1780.0	84.6	15.1	1186.0	566.0	2.139	4.067	1.655	1.256	2.861
	472	400.4	1747.0	99.5	26.3	1141.0	601.0	2.410	4.329	1.658	1.262	2.835
	473	410.9	1714.0	114.5	37.7	1197.0	639.0	2.502	4.233	1.626	1.253	2.809
	474	437.4	1682.0	129.4	49.1	1198.0	687.0	2.787	4.195	1.579	1.245	2.773
	475	475.1	1649.0	144.3	60.3	1163.0	742.0	3.038	4.060	1.503	1.224	2.729
	476	363.4	1783.0	84.6	15.1	1190.0	566.0	2.124	4.032	1.651	1.255	2.862
	477	399.7	1750.0	99.4	26.3	1141.0	600.0	2.400	4.315	1.657	1.262	2.836
	478	410.4	1718.0	114.4	37.7	1196.0	639.0	2.492	4.224	1.625	1.252	2.810
	479	437.3	1685.0	129.4	49.1	1195.0	687.0	2.780	4.190	1.578	1.245	2.773
	480	474.7	1652.0	144.3	60.3	1162.0	742.0	3.029	4.055	1.503	1.224	2.727

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
108	481	363.8	1785.0	84.5	15.1	1188.0	566.0	2.124	4.036	1.651	1.255	2.862
	482	399.9	1753.0	99.4	26.3	1180.0	600.0	2.399	4.315	1.657	1.262	2.836
	483	410.7	1720.0	114.4	37.7	1194.0	639.0	2.492	4.223	1.625	1.252	2.810
	484	437.5	1687.0	129.4	49.1	1194.0	686.0	2.779	4.189	1.578	1.245	2.773
	485	475.3	1655.0	144.3	60.3	1160.0	742.0	3.028	4.054	1.562	1.223	2.729
	486	423.4	1787.0	88.0	15.1	1204.0	571.0	2.620	4.660	1.686	1.274	2.857
	487	464.2	1754.0	105.5	26.3	1169.0	612.0	2.949	4.650	1.623	1.265	2.827
	488	490.5	1721.0	123.2	37.7	1190.0	661.0	3.114	4.452	1.554	1.244	2.790
	489	509.1	1688.0	140.9	49.1	1246.0	723.0	3.233	4.188	1.483	1.221	2.739
	490	553.7	1655.0	158.4	60.3	1219.0	793.0	3.572	3.998	1.395	1.191	2.684
	491	421.6	1790.0	87.9	15.1	1206.0	570.0	2.598	4.645	1.685	1.275	2.857
	492	464.7	1757.0	105.3	26.3	1162.0	611.0	2.949	4.652	1.623	1.265	2.827
	493	491.3	1723.0	122.9	37.7	1182.0	661.0	3.116	4.456	1.553	1.244	2.790
	494	510.2	1690.0	140.5	49.1	1236.0	721.0	3.238	4.195	1.483	1.222	2.740
	495	555.2	1657.0	158.0	60.3	1208.0	791.0	3.578	4.007	1.395	1.191	2.685
	496	420.9	1793.0	87.9	15.1	1206.0	572.0	2.587	4.635	1.685	1.274	2.857
	497	465.0	1760.0	105.3	26.3	1158.0	613.0	2.947	4.649	1.622	1.265	2.827
	498	492.1	1726.0	122.9	37.7	1176.0	663.0	3.117	4.457	1.553	1.244	2.790
	499	511.2	1693.0	140.5	49.1	1229.0	724.0	3.241	4.197	1.483	1.222	2.741
	500	556.5	1660.0	157.9	60.3	1201.0	794.0	3.581	4.011	1.395	1.191	2.686
	501	423.4	1795.0	87.9	15.1	1199.0	572.0	2.610	4.653	1.684	1.275	2.857
	502	467.1	1762.0	105.4	26.3	1154.0	613.0	2.956	4.652	1.620	1.264	2.827
	503	495.1	1729.0	123.0	37.7	1169.0	663.0	3.135	4.461	1.550	1.243	2.790
	504	514.6	1695.0	140.6	49.1	1220.0	724.0	3.264	4.292	1.479	1.221	2.740
	505	561.1	1662.0	158.1	60.3	1190.0	794.0	3.602	4.019	1.391	1.190	2.685
	506	425.5	1797.0	88.0	15.1	1194.0	572.0	2.630	4.668	1.684	1.275	2.857
	507	469.0	1764.0	105.5	26.3	1151.0	613.0	2.965	4.654	1.618	1.264	2.827
	508	497.8	1731.0	123.1	37.7	1163.0	663.0	3.150	4.465	1.547	1.243	2.790
	509	517.4	1698.0	140.8	49.1	1215.0	724.0	3.280	4.200	1.477	1.222	2.740
	510	564.8	1666.0	158.3	60.3	1183.0	794.0	3.616	4.024	1.388	1.189	2.684
	511	425.4	1797.0	88.0	15.1	1195.0	572.0	2.628	4.666	1.684	1.275	2.857
	512	469.0	1764.0	105.5	26.3	1151.0	614.0	2.965	4.653	1.618	1.264	2.827
	513	497.7	1731.0	123.2	37.7	1164.0	663.0	3.149	4.464	1.547	1.243	2.790
	514	517.4	1698.0	140.9	49.1	1215.0	725.0	3.279	4.203	1.476	1.220	2.739
	515	565.0	1666.0	158.4	60.3	1183.0	795.0	3.617	4.023	1.387	1.189	2.684
	516	424.9	1797.0	88.1	15.1	1197.0	573.0	2.622	4.669	1.683	1.275	2.857
	517	469.3	1764.0	105.7	26.3	1150.0	614.0	2.966	4.652	1.617	1.264	2.827
	518	498.1	1731.0	123.3	37.7	1164.0	664.0	3.151	4.462	1.546	1.243	2.789
	519	518.2	1698.0	141.0	49.1	1214.0	725.0	3.285	4.201	1.475	1.220	2.739
	520	565.3	1666.0	158.6	60.3	1183.0	795.0	3.616	4.020	1.386	1.189	2.684
	521	497.6	1799.0	92.6	15.1	1225.0	580.0	3.166	4.951	1.630	1.276	2.850
	522	550.1	1766.0	113.3	26.3	1187.0	630.0	3.584	4.817	1.538	1.251	2.813
	523	586.4	1732.0	134.3	37.7	1211.0	696.0	3.764	4.551	1.448	1.222	2.759
	524	613.3	1698.0	155.3	49.1	1268.0	776.0	3.884	4.216	1.364	1.188	2.692
	525	675.8	1665.0	176.0	60.3	1230.0	865.0	4.146	3.773	1.235	1.150	2.627
	526	497.3	1799.0	92.7	15.1	1226.0	580.0	3.162	4.947	1.630	1.276	2.850
	527	551.0	1766.0	113.4	26.3	1185.0	631.0	3.587	4.818	1.537	1.251	2.813
	528	587.5	1733.0	134.4	37.7	1208.0	696.0	3.769	4.552	1.447	1.222	2.758
	529	615.0	1699.0	155.4	49.1	1263.0	777.0	3.893	4.220	1.362	1.188	2.692
	530	677.8	1666.0	176.1	60.3	1225.0	865.0	4.155	3.768	1.232	1.149	2.627
	531	498.5	1799.0	92.7	15.1	1222.0	580.0	3.172	4.952	1.629	1.275	2.850
	532	551.8	1766.0	113.4	26.3	1183.0	631.0	3.592	4.821	1.536	1.251	2.813
	533	588.7	1733.0	134.4	37.7	1205.0	696.0	3.777	4.557	1.446	1.222	2.758
	534	616.4	1699.0	155.4	49.1	1260.0	777.0	3.904	4.225	1.361	1.188	2.692
	535	679.4	1666.0	176.1	60.3	1222.0	865.0	4.165	3.766	1.231	1.149	2.627
	536	499.2	1802.0	92.9	15.1	1221.0	580.0	3.171	4.947	1.627	1.276	2.849
	537	554.9	1768.0	113.7	26.3	1175.0	631.0	3.606	4.827	1.534	1.251	2.812
	538	593.5	1734.0	134.6	37.7	1193.0	697.0	3.805	4.570	1.442	1.221	2.758
	539	622.6	1700.0	155.5	49.1	1243.0	777.0	3.980	4.233	1.356	1.187	2.691
	540	687.6	1666.0	176.2	60.3	1202.0	866.0	4.209	3.754	1.222	1.143	2.627

ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/ 1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
108	541	581.6	1802.0	93.4	15.1	1214.0	581.0	3.187	4.987	1.624	1.275	2.848
	542	557.8	1769.0	114.1	26.3	1167.0	632.0	3.619	4.829	1.530	1.250	2.811
	543	598.0	1735.0	135.0	37.7	1181.0	698.0	3.830	4.576	1.438	1.220	2.757
	544	629.9	1702.0	155.9	49.1	1224.0	778.0	3.972	4.215	1.336	1.186	2.690
	545	696.5	1668.0	176.7	60.3	1181.0	867.0	4.255	3.734	1.211	1.147	2.625
	546	503.7	1805.0	93.9	15.1	1209.0	564.0	3.197	4.944	1.621	1.275	2.848
	547	561.5	1772.0	114.6	26.3	1159.0	636.0	3.634	4.833	1.526	1.249	2.811
	548	603.4	1737.0	135.5	37.7	1169.0	702.0	3.860	4.586	1.433	1.219	2.755
	549	637.7	1703.0	156.4	49.1	1206.0	763.0	4.006	4.195	1.335	1.185	2.689
	550	705.7	1670.0	177.1	60.3	1162.0	672.0	4.304	3.714	1.201	1.146	2.623
	551	501.7	1806.0	94.3	15.1	1204.0	565.0	3.174	4.920	1.622	1.274	2.847
	552	560.4	1772.0	114.8	26.3	1149.0	636.0	3.624	4.822	1.526	1.249	2.810
	553	603.5	1738.0	135.5	37.7	1155.0	702.0	3.858	4.585	1.433	1.219	2.755
	554	638.0	1705.0	156.2	49.1	1188.0	782.0	4.008	4.197	1.334	1.185	2.689
	555	705.6	1671.0	176.7	60.3	1106.0	870.0	4.300	3.721	1.202	1.147	2.625
	556	510.1	1813.0	95.4	15.1	1193.0	588.0	3.227	4.931	1.612	1.273	2.845
	557	571.9	1781.0	116.2	26.3	1135.0	632.0	3.672	4.834	1.515	1.246	2.808
	558	619.0	1748.0	137.2	37.7	1135.0	699.0	3.939	4.602	1.418	1.215	2.751
	559	658.0	1715.0	158.1	49.1	1159.0	779.0	4.080	4.129	1.306	1.181	2.684
	560	732.1	1682.0	178.9	60.3	1111.0	869.0	4.421	3.646	1.170	1.143	2.615
109	561	-120.4	522.0	-168.5	10.0	3207.0	199.0	1.035	1.449	1.109	1.301	5.868
	562	-129.3	511.0	-163.4	15.0	3776.0	210.0	1.030	1.379	1.055	.998	5.668
	563	-129.3	501.0	-158.4	19.9	4561.0	222.0	1.026	1.308	1.081	.995	5.460
	564	-129.5	490.0	-153.3	24.9	5747.0	236.0	1.021	1.235	1.065	.992	5.247
	565	39.1	479.0	-148.2	29.9	749.0	205.0	1.225	3.463	1.678	1.095	5.103
	566	-87.5	523.0	-165.3	10.0	2348.0	205.0	1.074	1.936	1.237	1.027	5.745
	567	-200.0	512.0	-158.5	15.0	4573.0	221.0	.965	.609	.937	.995	5.466
	568	-200.0	501.0	-151.6	19.9	4080.0	237.0	.959	.568	.891	.991	5.202
	569	-200.5	489.0	-144.7	24.9	3664.0	252.0	.953	.530	.874	.987	5.005
	570	106.8	478.0	-137.8	29.9	865.0	269.0	1.357	6.605	1.967	1.144	4.797
	571	-87.1	523.0	-162.0	10.0	3159.0	212.0	1.071	1.877	1.228	1.027	5.614
	572	100.5	512.0	-153.6	15.0	978.0	232.0	1.355	5.097	2.011	1.137	5.261
	573	-268.4	501.0	-145.1	19.9	2094.0	251.0	.903	.084	.749	.956	5.017
	574	-249.9	490.0	-136.6	24.9	2032.0	272.0	.896	.076	.730	.963	4.760
	575	154.8	478.0	-128.1	29.9	980.0	292.0	1.558	6.928	2.473	1.212	4.565
	576	82.5	526.0	-159.9	10.0	1115.0	216.0	1.319	4.936	1.944	1.124	5.526
	577	133.5	514.0	-150.3	15.0	1004.0	239.0	1.453	6.104	2.200	1.170	5.168
	578	-310.3	502.0	-140.8	19.9	1764.0	261.0	.872	.051	.680	.959	4.888
	579	-312.9	491.0	-131.2	24.9	1735.0	284.0	.863	.047	.661	.955	4.633
	580	184.0	479.0	-121.6	29.9	1073.0	308.0	3.112	19.080	4.076	1.559	4.419
	581	160.5	526.0	-157.3	10.0	951.0	222.0	1.590	8.798	2.610	1.209	5.421
	582	166.0	514.0	-146.9	15.0	1018.0	245.0	1.618	9.697	2.826	1.220	5.072
	583	165.0	503.0	-136.5	19.9	1117.0	271.0	1.597	8.551	2.733	1.219	4.759
	584	174.4	491.0	-126.1	24.9	1177.0	295.0	1.809	11.077	3.194	1.303	4.522
	585	178.8	479.0	-115.7	29.9	1263.0	322.0	2.241	12.582	3.482	1.436	4.295
	586	166.8	528.0	-154.7	10.0	1062.0	228.0	1.626	9.845	2.795	1.219	5.309
	587	171.3	516.0	-143.1	15.0	1150.0	253.0	1.652	10.681	3.094	1.251	4.961
	588	171.4	504.0	-131.6	19.9	1266.0	281.0	1.651	10.180	3.017	1.233	4.644
	589	189.2	492.0	-120.1	24.9	1311.0	310.0	3.061	26.842	4.435	1.532	4.384
	590	202.1	481.0	-108.5	29.9	1373.0	339.0	6.604	25.179	4.625	1.751	4.185
	591	183.2	536.0	-151.8	10.0	1139.0	233.0	1.784	14.429	3.323	1.259	5.213
	592	190.5	527.0	-139.2	15.0	1233.0	262.0	1.994	18.914	3.774	1.323	4.845
	593	200.5	519.0	-126.6	19.9	1321.0	292.0	3.743	22.352	4.132	1.592	4.537
	594	227.3	510.0	-114.0	24.9	1343.0	324.0	8.634	26.155	4.582	1.739	4.273
	595	244.6	502.0	-101.4	29.9	1400.0	357.0	9.489	23.760	4.389	1.730	4.070
	596	214.4	542.0	-148.7	10.0	1158.0	239.0	7.155	25.463	4.323	1.682	5.126
	597	240.0	534.0	-135.1	15.0	1202.0	271.0	8.692	30.380	4.707	1.695	4.721
	598	257.0	525.0	-121.5	19.9	1270.0	303.0	9.503	27.320	4.532	1.698	4.420
	599	284.5	517.0	-107.6	24.9	1302.0	338.0	10.533	24.352	4.248	1.677	4.177
	600	320.8	508.0	-98.2	29.9	1306.0	374.0	11.723	21.545	3.898	1.641	3.973

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
109	601	350.7	529.0	-147.0	10.0	857.0	243.0	12.581	32.262	4.294	1.605	5.077
	602	434.0	511.0	-133.2	15.0	808.0	276.0	15.085	26.762	3.650	1.565	4.678
	603	515.2	493.0	-119.3	19.9	772.0	310.0	17.399	22.454	3.131	1.539	4.366
	604	615.6	475.0	-105.4	24.9	722.0	345.0	20.285	18.786	2.651	1.510	4.133
	605	720.8	458.0	-91.5	29.9	680.0	382.0	23.224	15.649	2.276	1.491	3.935
	606	168.5	537.0	-150.1	10.0	1077.0	237.0	1.628	9.453	2.750	1.221	5.165
	607	182.9	529.0	-138.8	15.0	1130.0	263.0	1.766	13.880	3.352	1.261	4.832
	608	192.5	521.0	-127.5	19.9	1200.0	289.0	2.221	20.155	3.921	1.391	4.556
	609	218.1	513.0	-116.2	24.9	1212.0	318.0	8.110	25.534	4.898	1.743	4.305
	610	213.2	504.0	-104.9	29.9	1338.0	347.0	7.982	24.189	4.376	1.757	4.127
	611	170.4	537.0	-149.3	10.0	1098.0	238.0	1.639	9.776	2.798	1.223	5.144
	612	186.3	529.0	-137.9	15.0	1148.0	264.0	1.807	15.763	3.517	1.270	4.865
	613	200.4	521.0	-126.5	19.9	1202.0	291.0	3.641	21.357	4.080	1.583	4.534
	614	234.6	513.0	-115.1	24.9	1187.0	320.0	8.866	26.233	4.555	1.730	4.288
	615	222.4	505.0	-103.6	29.9	1338.0	350.0	8.445	24.212	4.456	1.751	4.107
	616	193.1	540.0	-146.1	10.0	1154.0	244.0	2.251	16.889	3.557	1.380	5.052
	617	210.3	531.0	-133.5	15.0	1214.0	274.0	7.209	22.514	4.178	1.708	4.688
	618	232.6	523.0	-120.9	19.9	1253.0	304.0	8.579	27.314	4.592	1.721	4.497
	619	261.3	514.0	-108.3	24.9	1268.0	335.0	9.844	24.793	4.384	1.703	4.185
	620	266.5	506.0	-95.7	29.9	1367.0	369.0	10.116	22.574	4.221	1.703	3.991
	621	206.1	546.0	-144.4	10.0	1169.0	248.0	6.115	19.567	3.856	1.667	5.002
	622	260.1	540.0	-131.3	15.0	1117.0	279.0	9.308	29.407	4.611	1.680	4.642
	623	283.7	535.0	-118.3	19.9	1159.0	311.0	10.127	26.133	4.343	1.671	4.306
	624	281.3	530.0	-105.2	24.9	1275.0	343.0	10.073	23.769	4.209	1.676	4.135
	625	328.6	524.0	-92.1	29.9	1238.0	378.0	11.469	21.022	3.816	1.630	3.948
110	626	87.6	481.0	-231.4	10.0	170.0	35.0	1.415	26.083	2.332	1.138	23.064
	627	79.9	476.0	-225.8	15.0	191.0	41.0	1.390	21.225	2.254	1.133	19.866
	628	72.3	472.0	-220.3	19.9	217.0	50.0	1.366	16.697	2.179	1.127	16.570
	629	74.4	467.0	-214.7	24.9	244.0	63.0	1.365	13.229	2.163	1.129	13.171
	630	81.5	463.0	-209.1	29.9	279.0	88.0	1.376	9.955	2.177	1.135	9.662
	631	119.5	480.0	-230.5	10.0	186.0	36.0	1.510	30.874	2.553	1.167	22.553
	632	109.4	476.0	-224.1	15.0	213.0	43.0	1.468	23.801	2.440	1.158	18.868
	633	103.4	472.0	-217.8	19.9	246.0	55.0	1.442	17.991	2.363	1.152	15.053
	634	106.5	467.0	-211.4	24.9	285.0	76.0	1.445	13.295	2.349	1.156	11.102
	635	112.6	463.0	-205.0	29.9	325.0	103.0	1.457	10.209	2.357	1.162	8.345
	636	145.8	480.0	-229.0	10.0	206.0	37.0	1.614	35.464	2.767	1.195	21.637
	637	134.8	476.0	-221.8	15.0	240.0	47.0	1.554	25.900	2.626	1.182	17.475
	638	128.8	471.0	-214.6	19.9	284.0	64.0	1.523	18.273	2.532	1.177	13.105
	639	131.5	467.0	-207.4	24.9	348.0	100.0	1.525	11.924	2.512	1.181	8.556
	640	138.5	462.0	-200.2	29.9	364.0	110.0	1.545	11.423	2.533	1.187	7.943
	641	169.1	480.0	-227.0	10.0	230.0	39.0	1.763	55.725	3.711	1.231	20.551
	642	158.6	476.0	-218.9	15.0	273.0	53.0	1.676	30.511	3.033	1.215	15.744
	643	153.0	471.0	-210.8	19.9	338.0	79.0	1.629	17.780	2.730	1.207	10.716
	644	156.5	466.0	-202.7	24.9	388.0	107.0	1.643	14.396	2.835	1.213	8.151
	645	164.1	462.0	-194.6	29.9	410.0	119.0	1.723	15.844	3.177	1.239	7.456
	646	182.4	480.0	-225.2	10.0	257.0	42.0	2.950	99.035	4.966	1.459	19.505
	647	173.0	475.0	-216.3	15.0	313.0	59.0	1.929	43.129	3.925	1.287	14.129
	648	169.9	471.0	-207.3	19.9	404.0	100.0	1.745	22.647	3.623	1.236	8.533
	649	170.5	466.0	-198.4	24.9	437.0	113.0	1.739	20.694	3.617	1.236	7.783
	650	177.8	461.0	-189.4	29.9	467.0	129.0	2.638	24.939	4.195	1.451	6.995
	651	183.6	481.0	-224.2	10.0	274.0	43.0	3.125	0.000	5.101	1.478	18.908
	652	174.1	476.0	-214.8	15.0	338.0	63.0	2.016	42.212	4.004	1.311	13.249
	653	170.4	471.0	-205.5	19.9	430.0	103.0	1.746	22.542	3.645	1.237	8.383
	654	172.6	466.0	-196.1	24.9	465.0	116.0	1.900	21.722	3.758	1.289	7.590
	655	180.7	461.0	-186.7	29.9	496.0	132.0	3.234	28.537	4.489	1.525	6.851
111	656	118.4	483.0	-225.7	10.0	197.0	41.0	1.500	26.581	2.515	1.166	19.821
	657	112.8	479.0	-219.2	15.0	227.0	51.0	1.474	20.256	2.436	1.161	15.934
	658	106.2	474.0	-212.7	19.9	269.0	70.0	1.445	14.268	2.353	1.155	11.904
	659	108.6	470.0	-206.1	24.9	318.0	101.0	1.445	10.082	2.333	1.158	8.438
	660	114.1	465.0	-199.6	29.9	332.0	109.0	1.456	9.605	2.341	1.162	7.890

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
111	661	187.3	483.0	-222.2	10.0	267.0	46.0	3.743	0.000	5.596	1.529	17.753
	662	181.1	479.0	-213.0	15.0	330.0	68.0	2.758	54.712	4.670	1.447	12.139
	663	176.9	474.0	-203.9	19.9	407.0	103.0	2.294	29.076	4.169	1.380	8.250
	664	178.3	469.0	-194.7	24.9	441.0	117.0	2.524	27.540	4.245	1.427	7.466
	665	184.7	465.0	-185.5	29.9	472.0	132.0	4.494	36.717	4.958	1.614	5.782
	666	197.1	487.0	-218.4	10.0	361.0	53.0	4.228	0.000	5.755	1.559	15.456
	667	190.8	481.0	-207.0	15.0	486.0	99.0	4.586	69.242	5.652	1.592	8.508
	668	192.4	476.0	-195.5	19.9	536.0	115.0	5.557	59.998	5.594	1.639	7.581
	669	204.2	471.0	-184.1	24.9	575.0	134.0	8.751	52.312	5.576	1.707	6.705
	670	225.0	465.0	-172.6	29.9	601.0	154.0	10.478	46.134	5.544	1.711	6.042
	671	221.1	490.0	-216.2	10.0	396.0	58.0	9.719	0.000	5.978	1.671	14.104
	672	289.5	484.0	-203.5	15.0	488.0	103.0	11.127	67.121	5.725	1.668	8.222
	673	233.4	478.0	-190.8	19.9	567.0	123.0	10.511	56.760	5.687	1.687	7.124
	674	228.6	472.0	-178.1	24.9	637.0	143.0	10.400	49.142	5.572	1.702	6.366
	675	276.5	466.0	-165.4	29.9	631.0	165.0	12.421	41.569	5.110	1.670	5.737
	676	232.9	491.0	-214.8	10.0	419.0	62.0	10.273	0.000	5.947	1.687	13.249
	677	277.1	485.0	-201.4	15.0	493.0	106.0	12.168	64.317	5.509	1.649	8.049
	678	252.5	480.0	-188.0	19.9	585.0	128.0	11.268	54.255	5.538	1.674	6.925
	679	247.0	474.0	-174.6	24.9	661.0	149.0	11.115	46.651	5.412	1.688	6.164
	680	310.5	468.0	-161.2	29.9	636.0	172.0	13.454	38.845	4.803	1.642	5.573
	681	265.8	500.0	-213.7	10.0	415.0	65.0	11.372	0.000	5.718	1.646	12.570
	682	286.8	492.0	-199.8	15.0	508.0	108.0	12.240	62.380	5.405	1.641	7.911
	683	295.1	484.0	-185.8	19.9	563.0	130.0	12.627	51.492	5.200	1.641	6.805
	684	328.5	477.0	-171.9	24.9	588.0	154.0	13.839	42.542	4.791	1.624	6.000
	685	364.5	469.0	-157.9	29.9	608.0	178.0	14.996	35.925	4.375	1.605	5.438
	686	287.7	503.0	-212.2	10.0	435.0	71.0	12.047	94.587	5.529	1.632	11.684
	687	310.4	495.0	-197.6	15.0	521.0	111.0	12.928	59.475	5.196	1.626	7.722
	688	323.5	488.0	-182.9	19.9	574.0	135.0	13.438	48.708	4.943	1.622	6.641
	689	358.5	480.0	-168.2	24.9	602.0	160.0	14.577	40.010	4.525	1.605	5.849
	690	393.3	472.0	-153.5	29.9	628.0	187.0	15.578	33.402	4.128	1.589	5.253
	691	328.1	507.0	-210.0	10.0	452.0	81.0	13.246	80.204	5.186	1.610	10.232
	692	357.1	500.0	-194.5	15.0	518.0	115.0	14.157	54.902	4.805	1.599	7.454
	693	370.9	493.0	-178.9	19.9	571.0	140.0	14.536	44.786	4.545	1.594	6.417
	694	412.1	487.0	-163.4	24.9	597.0	167.0	15.687	36.507	4.104	1.576	5.662
	695	445.1	480.0	-147.8	29.9	629.0	195.0	16.691	30.453	3.746	1.563	5.093
	696	419.2	471.0	-209.8	10.0	389.0	83.0	17.150	73.975	4.520	1.576	10.068
	697	485.1	459.0	-194.3	15.0	420.0	117.0	19.231	49.708	3.965	1.557	7.427
	698	525.7	447.0	-178.8	19.9	446.0	142.0	20.659	39.713	3.620	1.546	6.399
	699	592.1	435.0	-163.2	24.9	454.0	169.0	22.781	31.790	3.196	1.533	5.348
	700	630.5	423.0	-147.7	29.9	479.0	198.0	24.160	26.433	2.930	1.526	5.083
	701	383.5	490.0	-211.8	10.0	355.0	72.0	15.401	86.314	4.794	1.586	11.387
	702	449.3	471.0	-197.4	15.0	394.0	111.0	17.877	53.428	4.202	1.565	7.704
	703	486.4	452.0	-183.0	19.9	418.0	135.0	19.393	43.025	3.861	1.556	6.681
	704	530.6	433.0	-168.6	24.9	436.0	159.0	21.314	35.130	3.510	1.544	5.856
	705	546.6	415.0	-154.1	29.9	471.0	186.0	22.574	29.856	3.313	1.539	5.271
	706	251.4	495.0	-212.4	10.0	432.0	70.0	10.951	97.725	5.801	1.657	11.747
	707	285.7	489.0	-198.5	15.0	502.0	109.0	12.302	61.437	5.405	1.643	7.803
	708	237.7	483.0	-184.6	19.9	629.0	132.0	10.493	52.500	5.566	1.685	6.738
	709	309.9	477.0	-170.7	24.9	601.0	156.0	13.221	42.605	4.913	1.637	5.985
	710	284.5	471.0	-156.8	29.9	705.0	179.0	12.416	37.754	4.932	1.665	5.392
	711	120.9	493.0	-225.9	10.0	195.0	40.0	1.507	27.141	2.534	1.168	19.982
	712	120.4	488.0	-219.2	15.0	221.0	51.0	1.498	21.229	2.491	1.168	15.933
	713	119.5	484.0	-212.5	19.9	259.0	70.0	1.487	15.322	2.445	1.168	11.772
	714	113.7	479.0	-205.7	24.9	313.0	100.0	1.461	10.354	2.366	1.163	8.406
	715	111.9	475.0	-199.0	29.9	336.0	109.0	1.447	9.378	2.321	1.159	7.839
112	716	391.8	1771.0	63.4	15.1	579.0	173.0	2.419	5.030	1.799	1.289	2.965
	717	402.2	1767.0	86.6	26.3	654.0	198.0	2.444	4.528	1.693	1.272	2.838
	718	422.9	1762.0	110.1	37.7	692.0	217.0	2.569	4.323	1.627	1.255	2.819
	719	452.7	1758.0	133.5	49.1	718.0	241.0	2.750	4.075	1.542	1.234	2.762
	720	478.9	1754.0	156.7	60.3	757.0	270.0	2.812	3.714	1.447	1.203	2.688

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr^.4	Re/1000	ρb/ρw	μb/μw	kb/kw	C̄p/Cpb	Pr
112	721	400.0	1786.0	63.6	15.1	561.0	167.0	2.473	5.112	1.802	1.291	2.965
	722	412.5	1782.0	88.2	26.3	634.0	193.0	2.517	4.575	1.686	1.272	2.856
	723	434.6	1778.0	113.0	37.7	672.0	212.0	2.663	4.347	1.615	1.252	2.814
	724	466.0	1774.0	137.7	49.1	700.0	237.0	2.789	4.016	1.516	1.227	2.750
	725	500.4	1770.0	162.3	60.3	726.0	268.0	2.904	3.665	1.415	1.193	2.672
	726	406.4	1793.0	63.8	15.1	550.0	167.0	2.523	5.179	1.804	1.292	2.965
	727	419.0	1789.0	88.6	26.3	621.0	193.0	2.570	4.612	1.684	1.273	2.856
	728	442.1	1785.0	113.7	37.7	657.0	212.0	2.727	4.382	1.610	1.254	2.813
	729	474.8	1781.0	138.7	49.1	684.0	238.0	2.829	4.017	1.506	1.225	2.747
	730	516.9	1778.0	163.5	60.3	695.0	269.0	3.007	3.687	1.401	1.189	2.668
	731	409.2	1799.0	63.6	15.1	544.0	165.0	2.543	5.199	1.803	1.293	2.966
	732	423.3	1795.0	88.6	26.3	612.0	191.0	2.605	4.639	1.682	1.274	2.856
	733	446.1	1792.0	113.9	37.7	649.0	210.0	2.740	4.384	1.606	1.253	2.813
	734	481.9	1788.0	139.1	49.1	670.0	236.0	2.864	4.025	1.499	1.223	2.746
	735	524.1	1784.0	164.1	60.3	682.0	266.0	3.050	3.694	1.394	1.188	2.667
	736	408.4	1800.0	66.4	15.1	548.0	168.0	2.924	5.467	1.762	1.302	2.951
	737	465.5	1796.0	93.4	26.3	612.0	194.0	2.939	4.812	1.650	1.275	2.848
	738	494.6	1792.0	120.8	37.7	645.0	216.0	3.030	4.425	1.550	1.243	2.797
	739	538.3	1788.0	148.1	49.1	664.0	246.0	3.250	4.033	1.433	1.207	2.716
	740	591.0	1784.0	175.2	60.3	669.0	281.0	3.431	3.706	1.324	1.165	2.629
	741	452.1	1804.0	66.5	15.1	542.0	168.0	2.940	5.470	1.777	1.302	2.951
	742	468.6	1800.0	93.8	26.3	606.0	194.0	2.951	4.811	1.646	1.275	2.848
	743	494.8	1796.0	121.3	37.7	641.0	217.0	3.036	4.417	1.547	1.242	2.796
	744	541.7	1792.0	148.9	49.1	659.0	247.0	3.268	4.025	1.429	1.206	2.714
	745	597.1	1789.0	176.1	60.3	660.0	282.0	3.454	3.705	1.318	1.163	2.625
	746	455.0	1808.0	66.3	15.1	536.0	168.0	2.953	5.483	1.775	1.302	2.952
	747	471.6	1804.0	93.6	26.3	600.0	194.0	2.964	4.819	1.644	1.275	2.848
	748	500.5	1800.0	121.2	37.7	634.0	216.0	3.057	4.428	1.544	1.242	2.797
	749	546.7	1797.0	148.8	49.1	650.0	247.0	3.307	4.040	1.426	1.206	2.714
	750	603.8	1793.0	176.1	60.3	649.0	282.0	3.489	3.726	1.314	1.163	2.625
	751	457.4	1812.0	66.8	15.1	535.0	168.0	2.961	5.469	1.770	1.301	2.950
	752	474.2	1808.0	94.2	26.3	598.0	194.0	2.973	4.813	1.640	1.273	2.847
	753	504.1	1805.0	121.9	37.7	631.0	217.0	3.073	4.422	1.539	1.241	2.795
	754	551.7	1801.0	149.6	49.1	645.0	248.0	3.329	4.038	1.420	1.204	2.711
	755	610.2	1797.0	177.0	60.3	643.0	283.0	3.516	3.729	1.309	1.161	2.622
	756	510.9	1813.0	70.2	15.1	536.0	172.0	3.343	5.590	1.711	1.300	2.931
	757	533.9	1809.0	100.2	26.3	592.0	199.0	3.418	4.948	1.583	1.268	2.837
	758	573.7	1805.0	130.4	37.7	620.0	226.0	3.557	4.516	1.468	1.227	2.772
	759	635.1	1801.0	160.7	49.1	627.0	261.0	3.759	4.063	1.331	1.182	2.678
	760	710.4	1797.0	190.6	60.3	620.0	304.0	3.948	3.447	1.170	1.134	2.569
	761	513.5	1816.0	70.4	15.1	533.0	172.0	3.358	5.590	1.708	1.300	2.930
	762	535.9	1812.0	100.5	26.3	589.0	199.0	3.428	4.946	1.580	1.267	2.837
	763	577.9	1808.0	130.9	37.7	614.0	226.0	3.574	4.520	1.464	1.226	2.771
	764	638.3	1804.0	161.3	49.1	624.0	262.0	3.765	4.047	1.326	1.181	2.676
	765	713.7	1800.0	191.4	60.3	617.0	305.0	3.956	3.432	1.166	1.133	2.568
	766	515.8	1818.0	70.4	15.1	529.0	172.0	3.374	5.598	1.706	1.300	2.930
	767	538.7	1814.0	100.5	26.3	584.0	199.0	3.450	4.955	1.578	1.267	2.837
	768	581.6	1810.0	130.9	37.7	608.0	226.0	3.594	4.533	1.462	1.226	2.771
	769	640.9	1806.0	161.3	49.1	619.0	262.0	3.774	4.044	1.323	1.181	2.676
	770	718.6	1802.0	191.4	60.3	610.0	305.0	3.980	3.429	1.161	1.133	2.568
	771	517.2	1820.0	70.9	15.1	530.0	173.0	3.380	5.586	1.702	1.299	2.928
	772	540.8	1816.0	100.9	26.3	583.0	199.0	3.464	4.955	1.576	1.267	2.836
	773	584.2	1812.0	131.2	37.7	606.0	226.0	3.604	4.535	1.459	1.226	2.770
	774	643.2	1808.0	161.6	49.1	618.0	262.0	3.779	4.036	1.319	1.180	2.675
	775	722.7	1805.0	191.6	60.3	607.0	305.0	3.999	3.423	1.157	1.132	2.567
	776	567.8	1820.0	73.7	15.1	527.0	176.0	3.782	5.730	1.652	1.298	2.912
	777	599.6	1816.0	105.9	26.3	572.0	203.0	3.839	5.123	1.525	1.258	2.828
	778	653.9	1812.0	138.5	37.7	592.0	234.0	3.981	4.504	1.374	1.213	2.749
	779	726.9	1808.0	171.0	49.1	598.0	274.0	4.184	3.798	1.204	1.164	2.644
	780	827.6	1804.0	203.3	60.3	578.0	323.0	4.422	3.168	1.041	1.109	2.534

OF POOR QUALITY

TABLE XII (CONT.)

Test Number HTB6-797-	ID Number	Wall T Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr^.4	Re/1000	ρb/ρw	μb/μw	kb/kw	Cp/Cpb	Pr
112	781	571.8	1823.0	74.1	15.1	525.0	176.0	3.801	5.732	1.647	1.297	2.909
	782	603.7	1819.0	106.5	26.3	568.0	203.0	3.860	5.129	1.521	1.257	2.827
	783	656.4	1815.0	139.2	37.7	591.0	235.0	3.984	4.485	1.369	1.212	2.747
	784	732.4	1811.0	171.9	49.1	594.0	275.0	4.201	3.777	1.196	1.163	2.641
	785	838.7	1807.0	204.3	60.3	570.0	325.0	4.469	3.146	1.031	1.107	2.530
	786	574.0	1826.0	74.0	15.1	521.0	176.0	3.809	5.742	1.646	1.297	2.910
	787	606.0	1821.0	106.4	26.3	564.0	203.0	3.871	5.138	1.520	1.257	2.828
	788	657.5	1817.0	139.2	37.7	588.0	235.0	3.986	4.483	1.368	1.212	2.747
	789	732.7	1812.0	171.9	49.1	593.0	275.0	4.199	3.778	1.196	1.163	2.641
	790	849.7	1808.0	204.3	60.3	559.0	324.0	4.529	3.140	1.022	1.107	2.530
	791	572.1	1828.0	74.1	15.1	523.0	176.0	3.792	5.727	1.647	1.297	2.910
	792	604.3	1824.0	106.5	26.3	566.0	203.0	3.853	5.127	1.521	1.257	2.828
	793	657.1	1820.0	139.2	37.7	588.0	235.0	3.978	4.483	1.368	1.212	2.747
	794	735.5	1815.0	171.8	49.1	594.0	275.0	4.183	3.780	1.199	1.163	2.642
	795	862.2	1811.0	204.2	60.3	548.0	324.0	4.598	3.137	1.013	1.107	2.531
	796	629.0	1829.0	76.8	15.1	516.0	180.0	4.169	5.872	1.590	1.294	2.894
	797	669.6	1825.0	111.2	26.3	552.0	207.0	4.212	5.068	1.435	1.250	2.819
	798	735.4	1820.0	145.9	37.7	570.0	243.0	4.393	4.278	1.261	1.201	2.725
	799	825.0	1816.0	180.6	49.1	571.0	288.0	4.596	3.558	1.091	1.151	2.609
	800	986.8	1811.0	215.0	60.3	517.0	343.0	5.381	2.898	.907	1.085	2.494
	801	632.2	1830.0	77.2	15.1	514.0	180.0	4.182	5.852	1.583	1.294	2.891
	802	672.3	1826.0	111.7	26.3	550.0	207.0	4.222	5.054	1.430	1.249	2.818
	803	739.1	1822.0	146.6	37.7	568.0	244.0	4.402	4.260	1.256	1.200	2.723
	804	821.4	1818.0	181.5	49.1	576.0	289.0	4.564	3.544	1.092	1.150	2.605
	805	1034.3	1813.0	216.1	60.3	491.0	345.0	5.765	2.862	.878	1.083	2.490
	806	633.2	1833.0	77.7	15.1	515.0	181.0	4.179	5.825	1.579	1.293	2.888
	807	673.0	1828.0	112.2	26.3	550.0	208.0	4.217	5.043	1.428	1.249	2.817
	808	733.7	1824.0	147.0	37.7	574.0	244.0	4.368	4.256	1.260	1.199	2.721
	809	818.7	1820.0	181.8	49.1	579.0	289.0	4.542	3.542	1.094	1.150	2.604
	810	1076.4	1815.0	216.2	60.3	466.0	345.0	6.200	2.842	.854	1.083	2.489
	811	631.1	1835.0	77.1	15.1	515.0	180.0	4.166	5.852	1.585	1.294	2.892
	812	674.1	1831.0	111.6	26.3	547.0	207.0	4.223	5.051	1.428	1.250	2.818
	813	730.5	1826.0	146.5	37.7	576.0	243.0	4.351	4.267	1.265	1.200	2.723
	814	828.7	1822.0	181.4	49.1	569.0	288.0	4.597	3.543	1.087	1.150	2.606
	815	1107.3	1818.0	216.0	60.3	450.0	344.0	6.566	2.834	.838	1.083	2.490
	816	632.0	1837.0	77.1	15.1	514.0	180.0	4.165	5.846	1.584	1.294	2.892
	817	677.4	1833.0	111.7	26.3	544.0	207.0	4.237	5.047	1.424	1.250	2.819
	818	734.8	1829.0	146.5	37.7	571.0	243.0	4.367	4.264	1.261	1.200	2.723
	819	842.1	1824.0	181.4	49.1	557.0	288.0	4.671	3.537	1.076	1.151	2.606
	820	1136.5	1820.0	215.9	60.3	435.0	344.0	6.952	2.825	.824	1.084	2.491
	821	630.7	1839.0	77.0	15.1	513.0	180.0	4.154	5.851	1.586	1.294	2.893
	822	678.5	1835.0	111.4	26.3	541.0	207.0	4.241	5.050	1.424	1.250	2.819
	823	738.5	1830.0	146.2	37.7	565.0	243.0	4.384	4.269	1.258	1.201	2.724
	824	854.2	1826.0	180.9	49.1	545.0	287.0	4.744	3.540	1.068	1.152	2.608
	825	1149.8	1821.0	215.3	60.3	427.0	343.0	7.152	2.830	.818	1.085	2.493
	826	636.9	1833.0	78.0	15.1	510.0	181.0	4.198	5.813	1.572	1.293	2.886
	827	682.9	1828.0	112.4	26.3	538.0	208.0	4.276	5.031	1.415	1.249	2.817
	828	747.6	1824.0	147.1	37.7	558.0	244.0	4.436	4.243	1.246	1.200	2.721
	829	876.5	1820.0	181.8	49.1	529.0	289.0	4.891	3.507	1.047	1.150	2.604
	830	1164.5	1815.0	216.2	60.3	421.0	345.0	7.380	2.801	.809	1.082	2.489
	831	478.5	1832.0	69.1	15.1	510.0	171.0	3.061	5.447	1.738	1.298	2.938
	832	503.5	1828.0	96.8	26.3	555.0	196.0	3.143	4.858	1.610	1.271	2.843
	833	539.5	1824.0	124.8	37.7	579.0	219.0	3.320	4.479	1.506	1.236	2.789
	834	622.2	1819.0	152.7	49.1	551.0	251.0	3.714	4.214	[illegible]	1.194	2.700
	835	842.3	1815.0	180.4	60.3	420.0	287.0	4.701	3.551	1.077	1.152	2.609
	836	505.1	1827.0	69.2	15.1	479.0	163.0	3.273	5.577	1.719	1.300	2.937
	837	537.5	1823.0	97.2	26.3	514.0	187.0	3.439	5.003	1.588	1.271	2.843
	838	575.7	1819.0	125.4	37.7	534.0	210.0	3.570	4.617	1.483	1.233	2.787
	839	658.1	1815.0	153.6	49.1	514.0	241.0	3.899	4.173	1.324	1.191	2.698
	840	904.1	1811.0	181.5	60.3	386.0	276.0	5.101	3.490	1.026	1.150	2.605

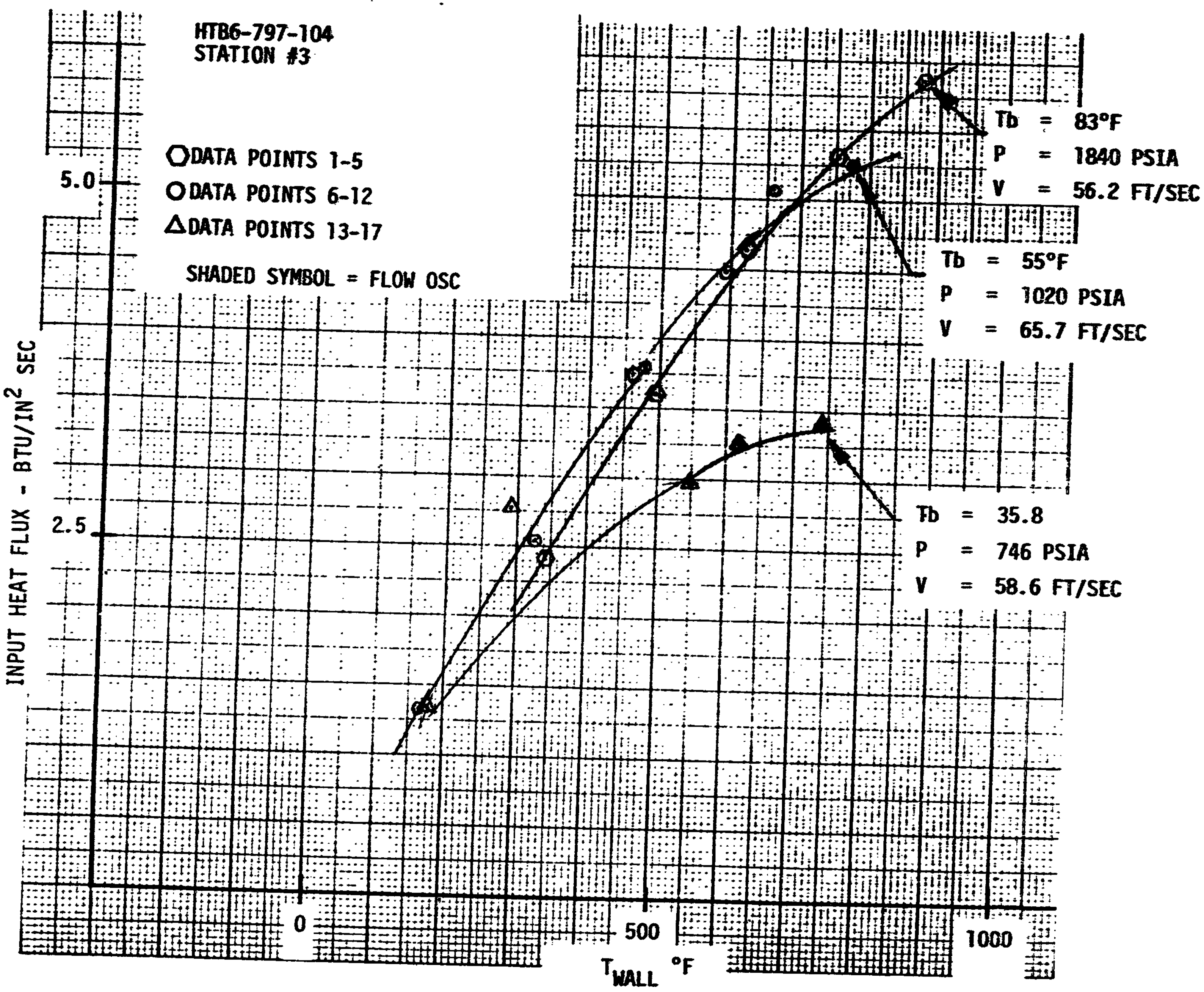


Figure 14. Typical Supercritical Pressure Heat Transfer Test Results

ORIGINAL PAGE IS
OF POOR QUALITY

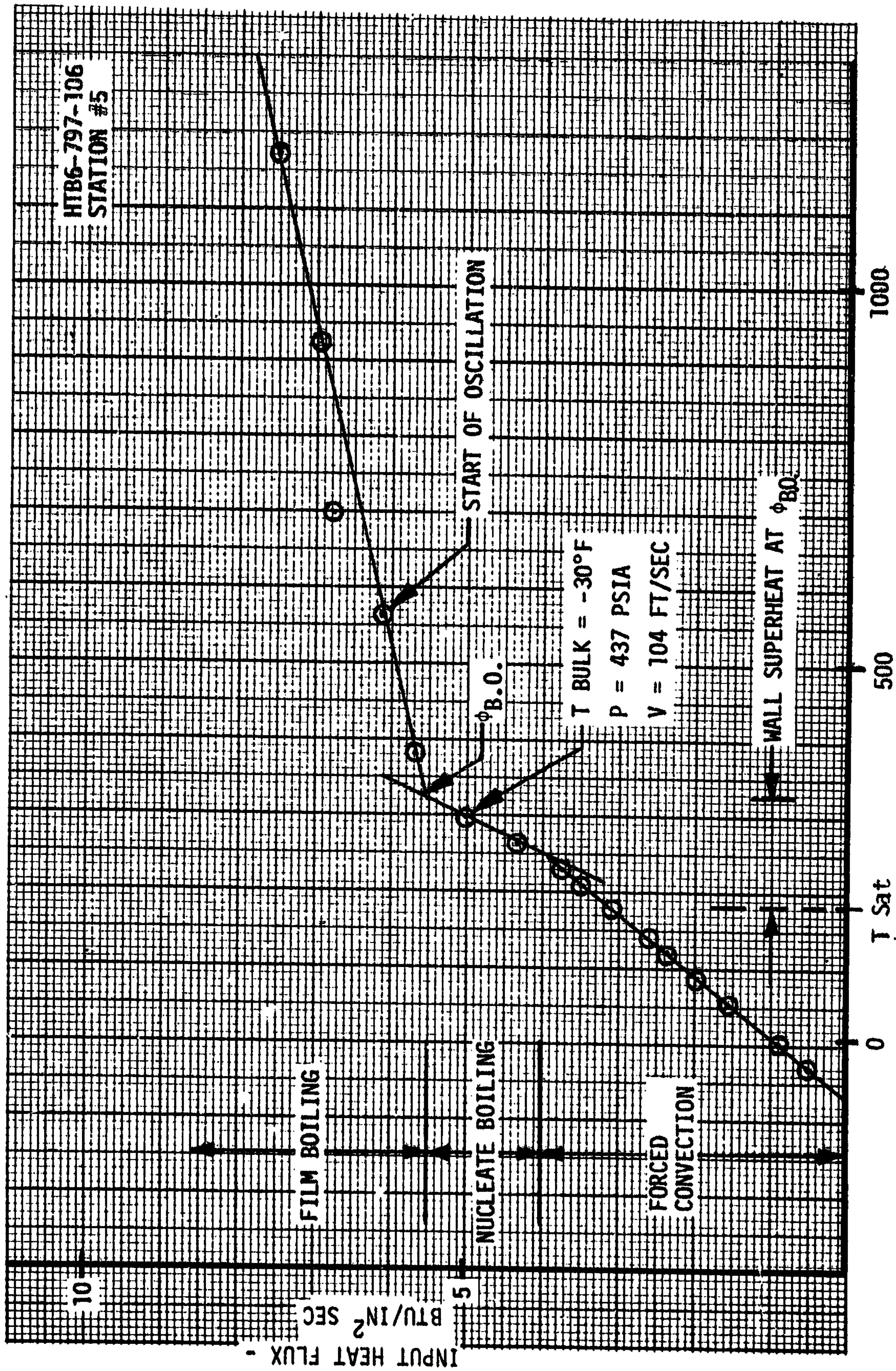


Figure 15. Typical Subcritical Pressure Heat Transfer Test Results

ORIGINAL PAGE IS
OF POOR QUALITY

boiling from the saturation temperature to the critical heat flux, and film boiling.

Three tests were dedicated to evaluating coking behavior. Figure 16 shows the measured temperature responses with various heat inputs; the gradual increase in temperature reflects the build-up of the coke layer, i.e., reduced cooling effectiveness of the fluid flow.

6. Data Correlation

Forced Convection

Forced convection heat transfer data were correlated by using the following equation:

$$Nu_b = (K)\,(Re_b)^a\,(Pr)^c\,\left(\frac{\rho_b}{\rho_w}\right)^d\left(\frac{\mu_b}{\mu_w}\right)^e\left(\frac{k_b}{k_w}\right)^f\left(\frac{\overline{C}_p}{C_{p_b}}\right)^g\left(\frac{P}{P_{crit}}\right)^h\left(1+\frac{2}{L/D}\right)$$

where:

Nu	=	Nusselt number
Re	=	Reynolds number
Pr	=	Prandtl number
ρ	=	Density
μ	=	Viscosity
k	=	Thermal conductivity
Cp	=	Specific heat
K	=	Experimental determined constant
P	=	Pressure
P_{crit}	=	Critical pressure
L/D	=	Length/diameter from initiation of heating

and subscripts:

b - denotes property evaluated at bulk temperature
w - denotes property evaluated at wall temperature

The constants k, a, c, d, e, f, g, and h were determined from the forced convection data by using a multiple regression analysis computer program.

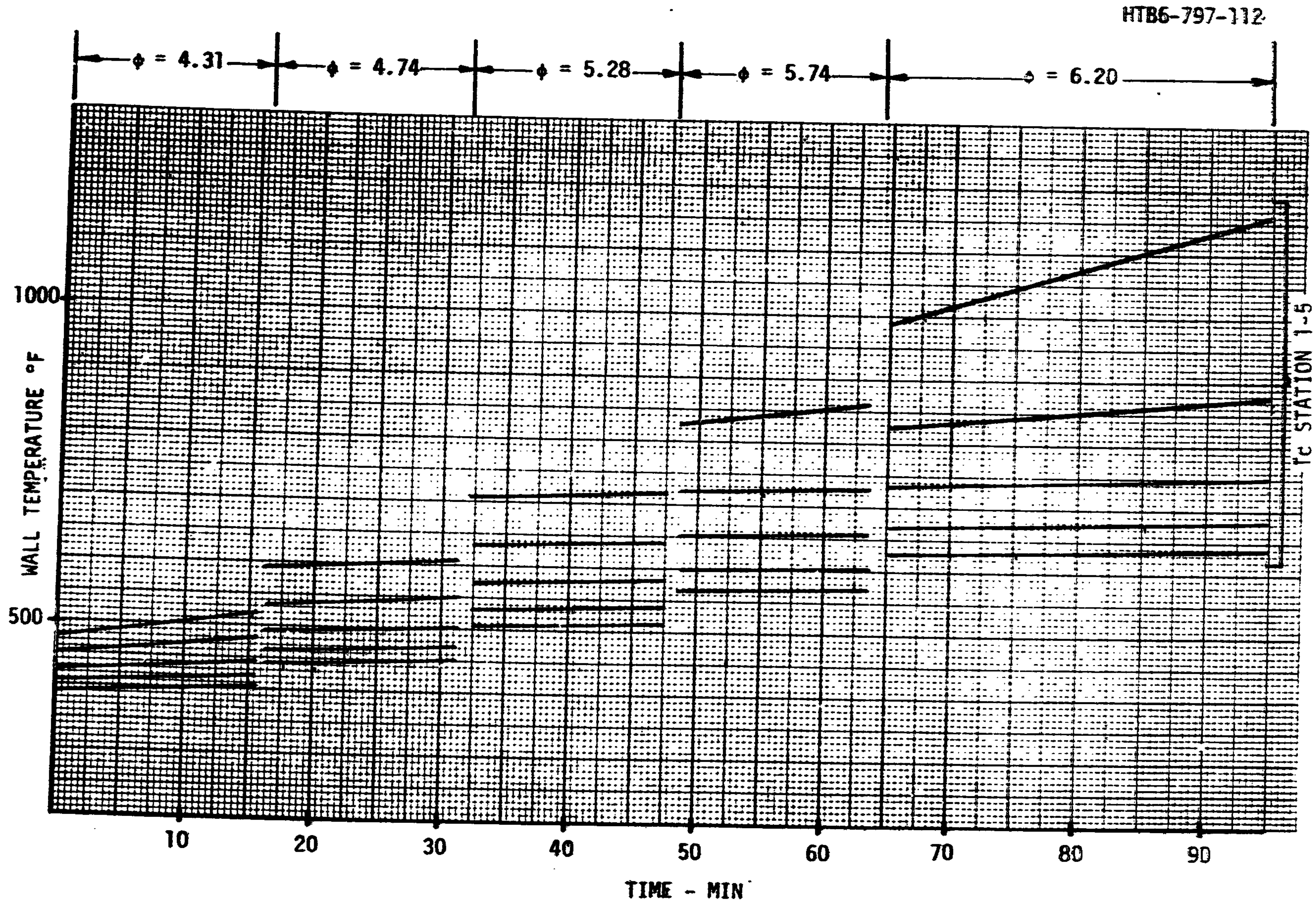


Figure 16. Typical Coking Test Results

Five cases were analyzed, as follows:

Case Number	Coefficients / Exponents								STD Deviation	Comments
	K	a	c	d	e	f	g	h		
1	.00538	.90	.4*	-.125	.242	.193	-.395	-.024	.130	All forced convection data
2	.00145	1.0*	.4*	-.227	.357	.069	-.299	-.037	.130	All forced convection data Reynolds number fixed
3	.00545	.898	.4*	-.114	.228	.267	-.526	0*	.130	All forced convection data (P/P_{crit}) removed
4	.00532	.889	.4*	-.129	.351	.0995	-.432	0*	.127	Supercritical data (P/P_{crit}) removed
5	.00568	.876	.4*	.120	-.142	.828	-.368	.254	.121	Supercritical data with (P/P_{crit}) term

*Denotes exponent held constant in analysis

Cases 1, 2, and 3 utilized the data from all twelve tests. In cases 4 and 5, tests 106, 109, 110 and 111 were deleted. In all cases data points influenced by oscillations or poor energy balance were not used.

Figures 17 and 18 plot the recommended forced convection correlations based on all data and supercritical data only (cases 3 and 5).

<u>Nucleate Boiling and Burnout Heat Flux</u>

Burnout heat flux data are plotted in Figure 19 and correlated by:

$$\phi_{B.O.} = 0.5 + 0.00027 \ V \ \Delta T_{sub}$$

where: $\phi_{B.O.}$ = Burnout heat flux - Btu/in.^{2} sec

V = Fluid velocity - ft/sec

ΔT_{sub} = (T saturation - T bulk) - °F

Nucleate boiling data were correlated in the following manner:

$$\phi_T = \phi_{F.C.} + \phi_{Nuc}$$

ORIGINAL PAGE IS
OF POOR QUALITY

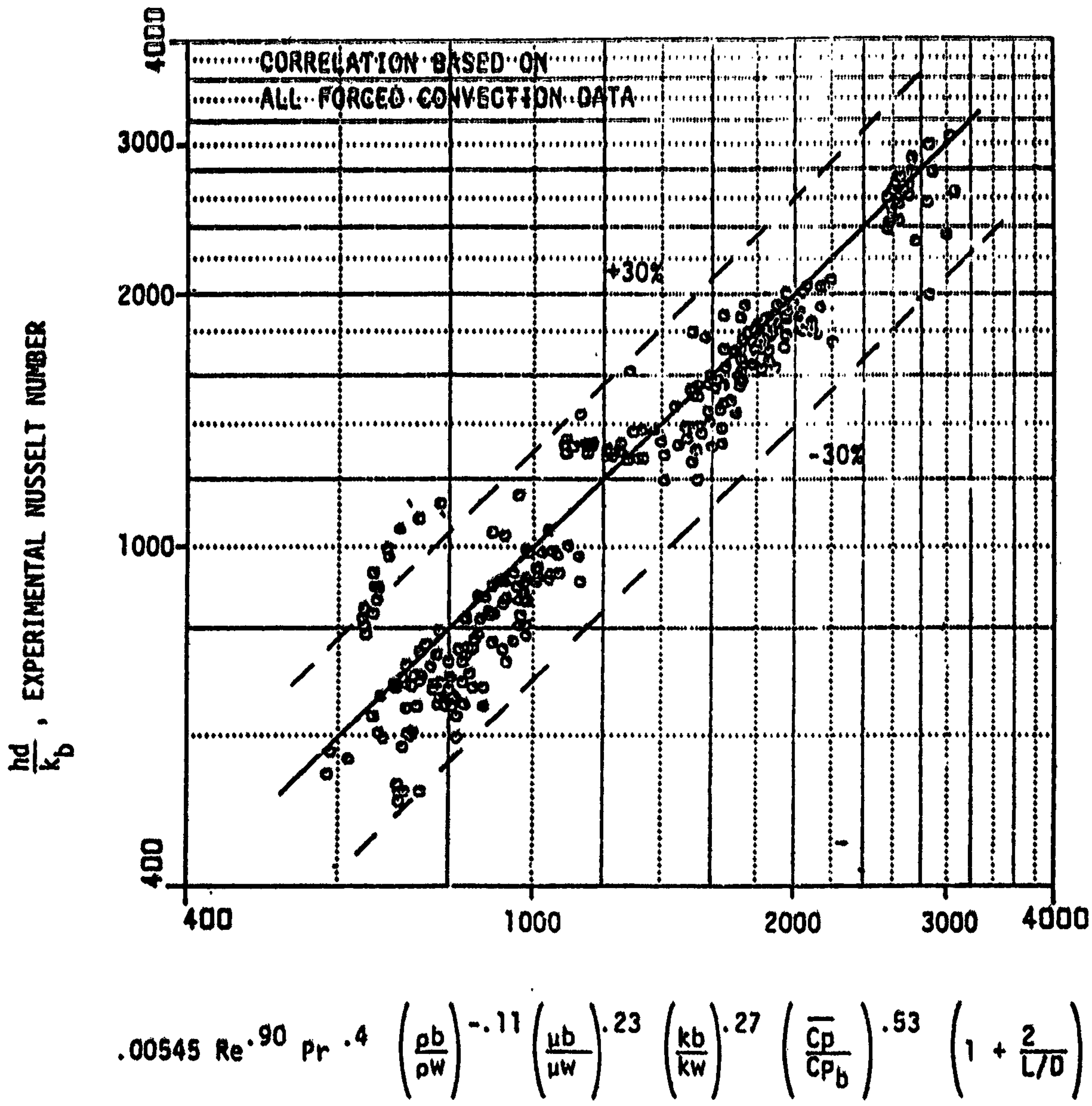
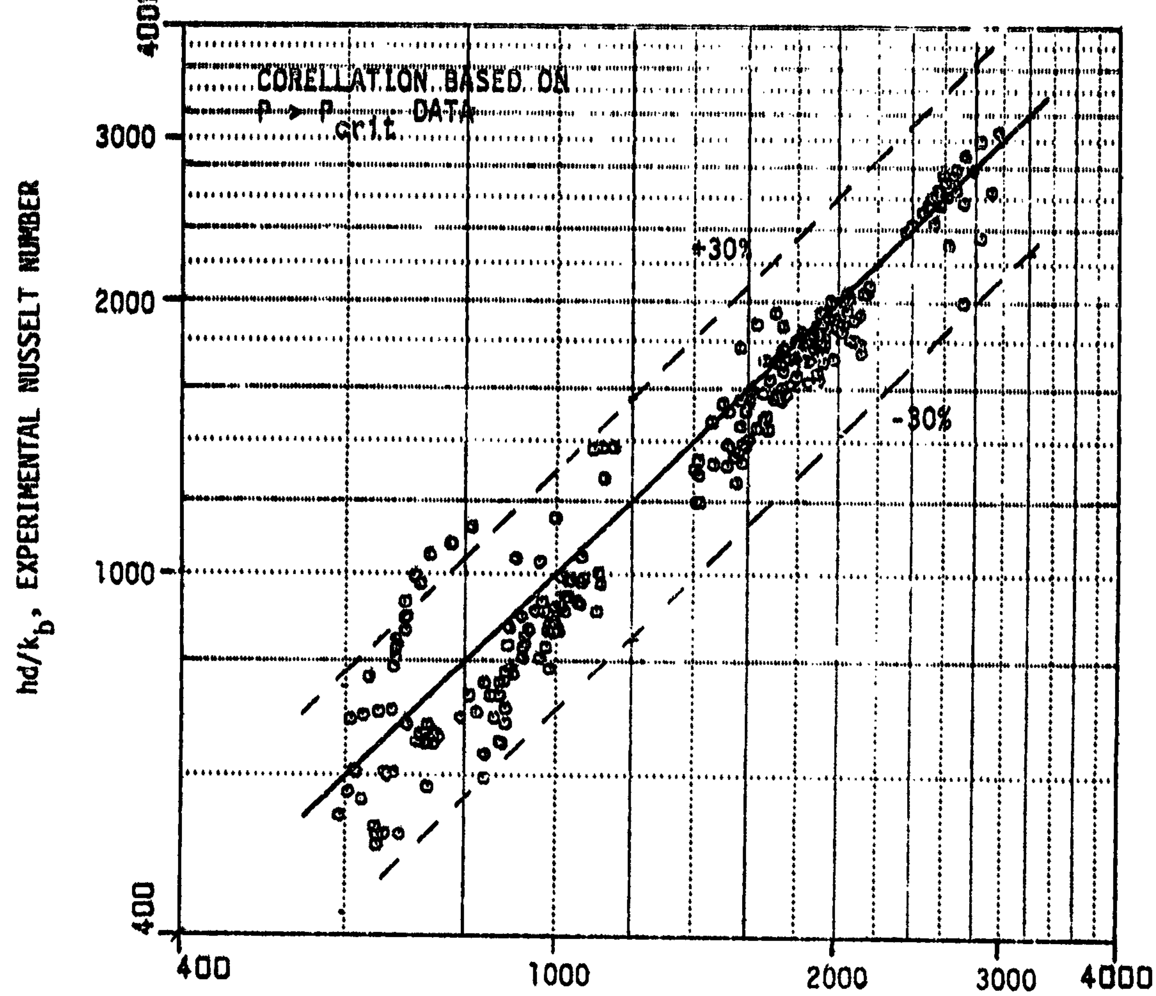


Figure 17. Forced Convection Correlation Based on All Data

ORIGINAL PAGE IS
OF POOR QUALITY



$$.00569\ Re_b^{.88}\ Pr_b^{.4} \left(\frac{\rho b}{\rho w}\right)^{.12} \left(\frac{\mu b}{\mu w}\right)^{-.14} \left(\frac{kb}{kw}\right)^{.83} \left(\frac{\overline{Cp}}{Cp_b}\right)^{-.37} \left(\frac{P}{Pcr}\right)^{.25} \left(1 + \frac{2}{L/D}\right)$$

Figure 18. Forced Convection Correlation Based on Supercritical Pressure Data

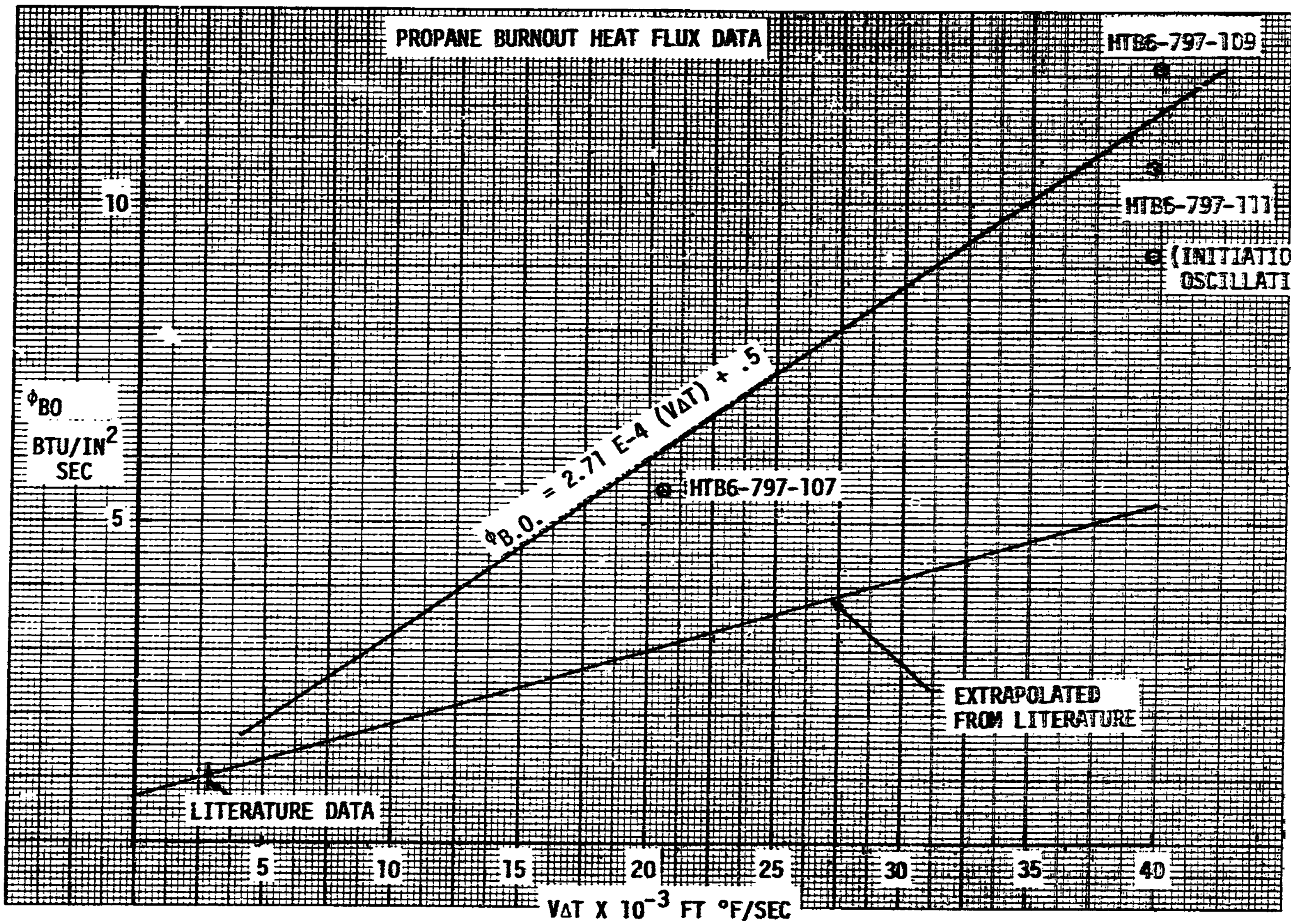


Figure 19. Burnout Heat Flux Correlation

where: ϕ_T = Total measured heat flux - Btu/in.^{2} sec

$\phi_{F.C.}$ = Assumed forced convection component when

$T_{wall} > T_{sat}$ - Btu/in.^{2} sec

ϕ_{Nuc} = Residual attributed to nucleate boiling mechanism - Btu/in.^{2} sec

The forced convection effect was calculated from

$$\phi_{FC} = h_{F.C.} \ (T_{sat} - T_{bulk})$$

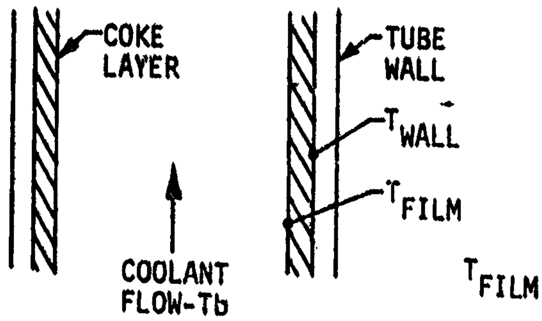
The forced convection coefficient $h_{F.C.}$ was calculated at $T_{wall} = T_{sat}$

O_{Nuc} was then plotted versus wall superheat $(T_{wall} - T_{sat})$. The results are shown in Figure 20.

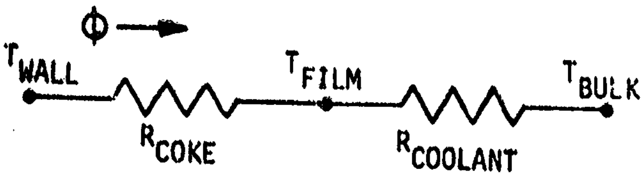
Coking Correlation

Coking data are plotted in Figure 21 in the form of coking rate versus the reciprocal of absolute temperature. A dashed line representing RP-1 rates (Ref. 11) is shown as a comparison.

Coking rates were calculated from the test data using the following model:



TEST SECTION



HEAT MODEL

ORIGINAL PAGE IS
OF POOR QUALITY

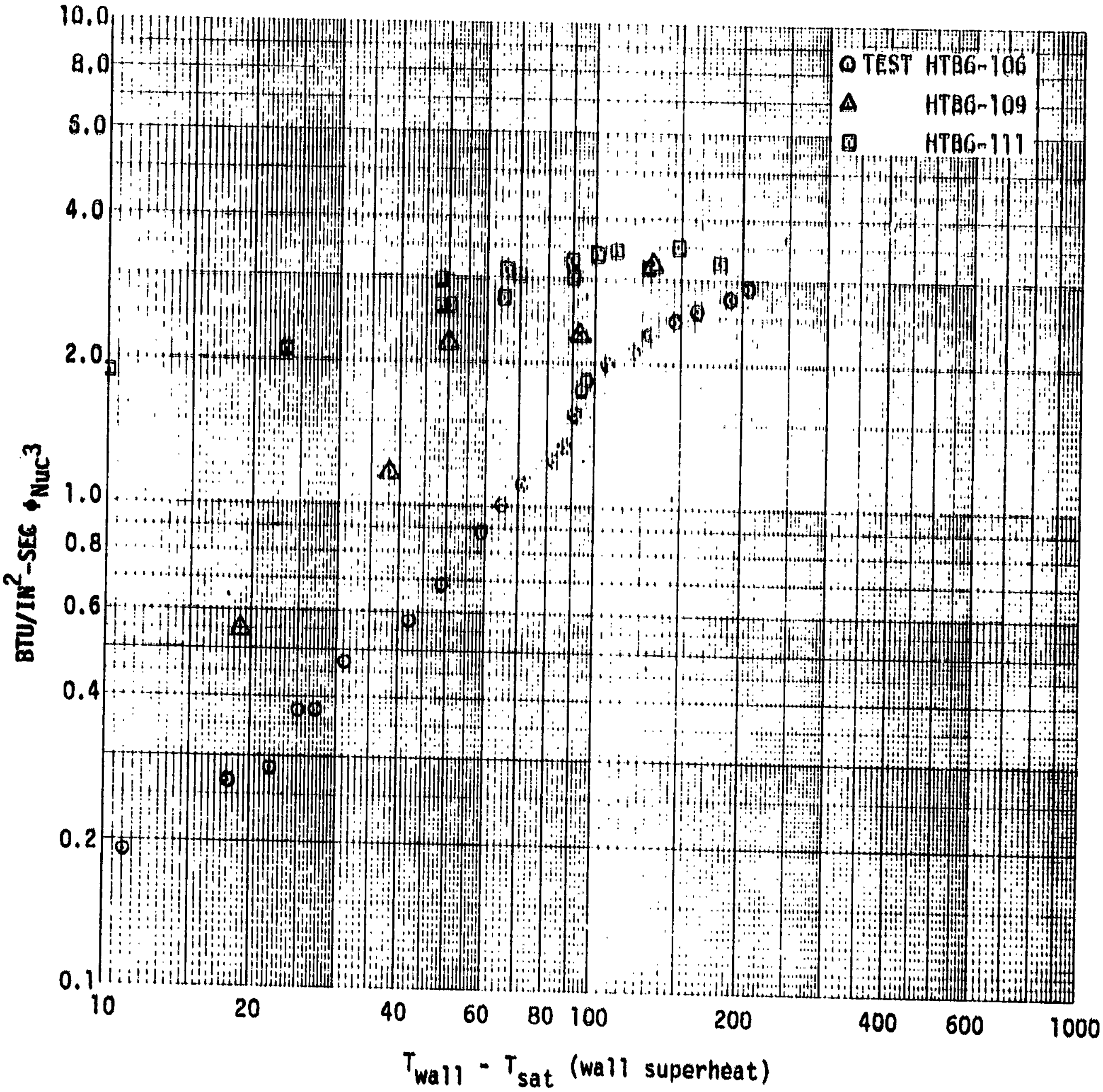


Figure 20. Nucleate Boiling Data

ORIGINAL PAGE IS
OF POOR QUALITY

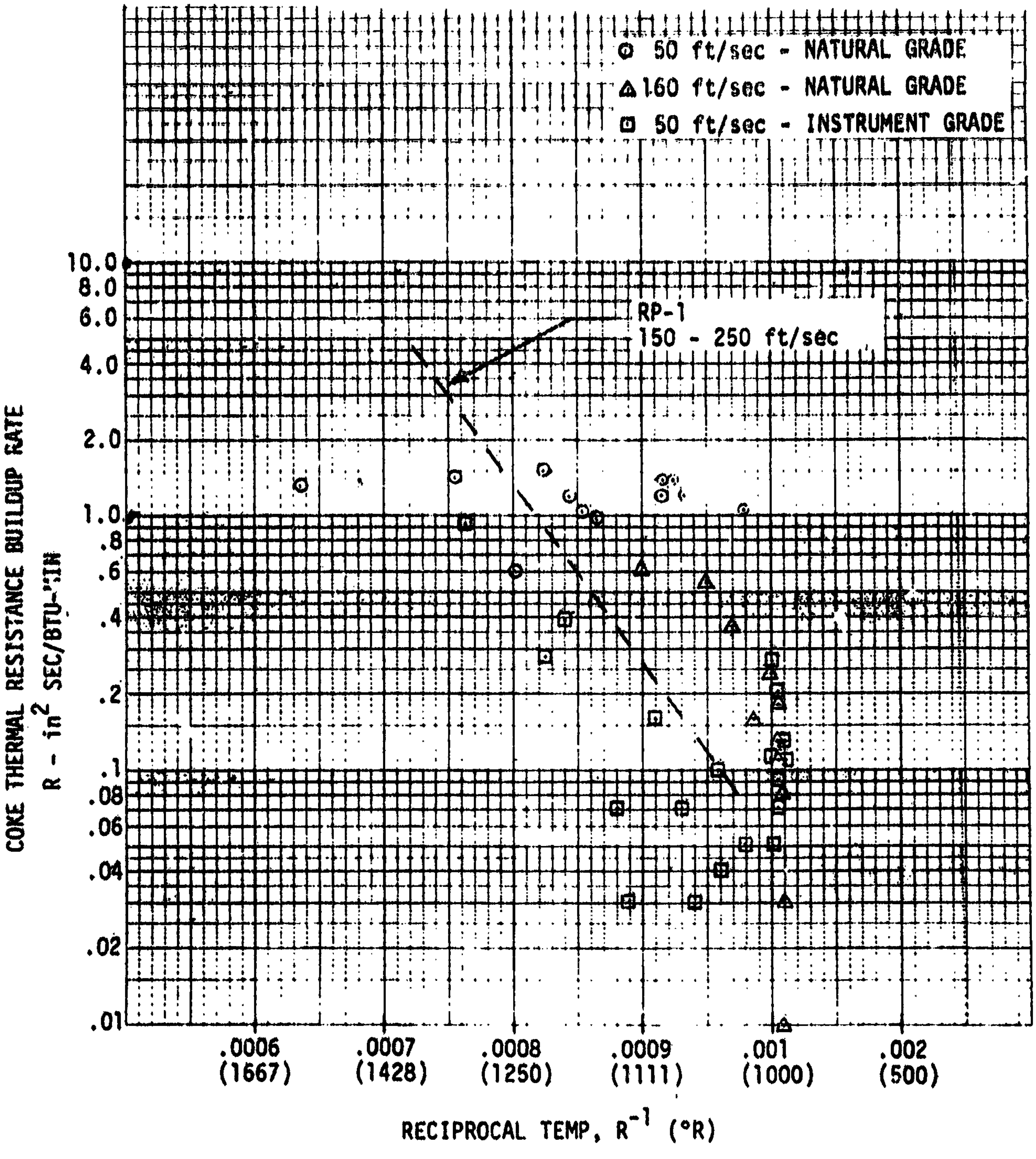


Figure 21. Propane Coking Rates

In this model:

T_{wall}	=	Calculated inside tube wall temperature (from test data)
T_{film}	=	Effective coolant film temperature
T_{bulk}	=	Bulk temperature of coolant (from test data)
$\emptyset$	=	Heat flux (from test data)
$R_{coolant}$	=	1/h, where h is the measured heat transfer coefficient
R_{coke}	=	Thermal resistance of coke layer

T_{film} is assumed to be the reference temperature at which the coking is occurring. It is calculated as

$$T_{film} = T_{wall} - (R_{coke}\ \emptyset)$$

or

$$T_{film} = T_b + (R_{coolant}\ \emptyset)$$

Initially $R_{coke} = 0$ and $T_{film} = T_{wall}$.

As coke develops on the tube wall, T_{film} is calculated as:

$$T_{film} = T_b + (R_{coolant}\ \emptyset)$$

At constant $\emptyset$, T_b and $R_{coolant}$ are also assumed constant, therefore T_{film} remains constant and R_{coke} is calculated from $R_{coke} = (T_{wall} - T_{film})/\emptyset$

R_{coke} is measured as a function of time and a coking rate defined as

$$\frac{R_{coke}}{\Delta t}$$

at the effective temperature, T_{film}

Upon change of power level, $\emptyset$, a new T_{film} is calculated as: $T_{film} = T_{wall}\ (R_{coke}$ [current value] $\emptyset)$ whereupon the procedure is repeated.

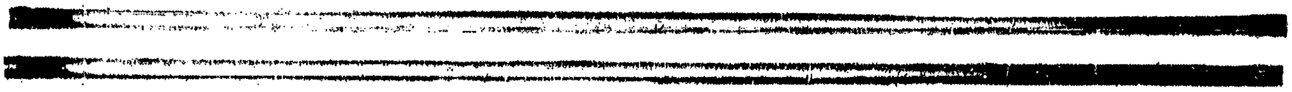
7. <u>Test Section Inspection</u>

Test sections used for the supercritical and cooling test series were split into two halves, as shown in Figures 22 and 23.

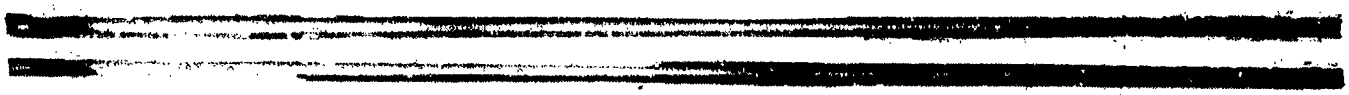
Small amounts of coke can be seen in some of the supercritical test sections (short duration exposure), while blackened tubes were characteristic of the low velocity coking tests.

ORIGINAL PAGE IS
OF POOR QUALITY

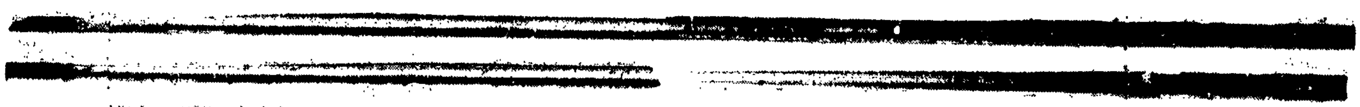
[illegible]



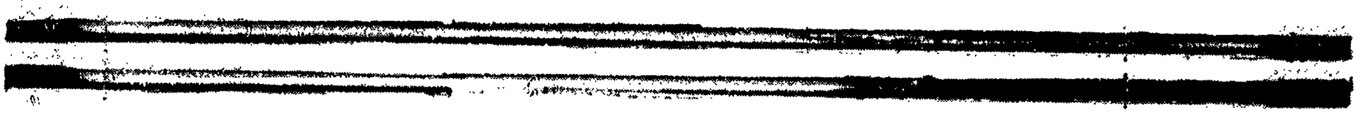
TEST: [illegible]
VELOCITY [illegible]
$\dot{q}_{MAX}$ [illegible]
$T_{WALL\ MAX}$ [illegible]



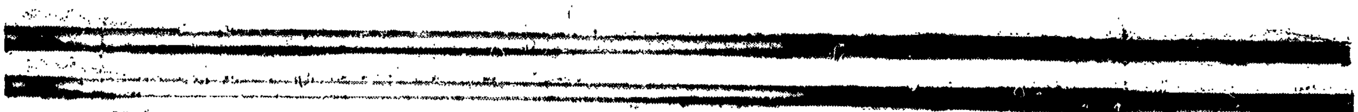
TEST: [illegible]
VELOCITY [illegible]
$\dot{q}_{MAX}$ = 10.4 BTU/IN^2-SEC
$T_{WALL\ MAX}$ [illegible]



TEST: HTB6-797-103
VELOCITY = 100 FT/SEC
$\dot{q}_{MAX}$ = 7.0 BTU/IN^2-SEC
$T_{WALL\ MAX}$ = 1108°F



TEST: HTB6-797-104
VELOCITY = 50 FT/SEC
$\dot{q}_{MAX}$ = 5.6 BTU/IN^2-SEC
$T_{WALL\ MAX}$ = 1086°F



TEST: HTB6-797-105
VELOCITY = 100 FT/SEC
$\dot{q}_{MAX}$ = 10.5 BTU/IN^2-SEC
$T_{WALL\ MAX}$ = [illegible]

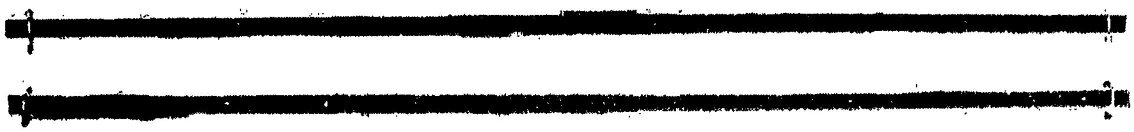
ORIGINAL PAGE IS
OF POOR QUALITY

TEST SECTIONS - COKING SERIES

TUBE MATERIAL: MONEL K500

TUBE DIMENSION: .125 IN. O.D. x .015 IN. WALL x 5.97 IN.

→ FLOW



TEST: HTB6-797-107

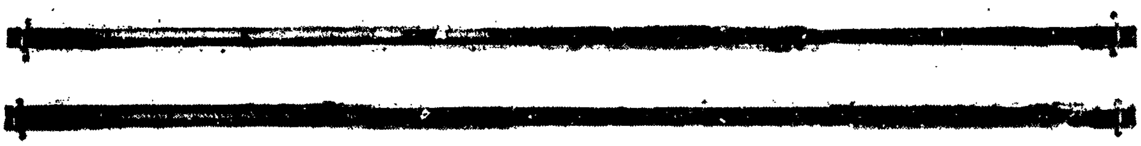
VELOCITY = 48 FT/SEC

PRESSURE = 1300 PSIA

$T_{WALL\ MAX}$ = 1220°F

ϕ_{MAX} = 5.8 BTU/IN^2-SEC

PROPANE GRADE: NATURAL



TEST: HTB6-797-108

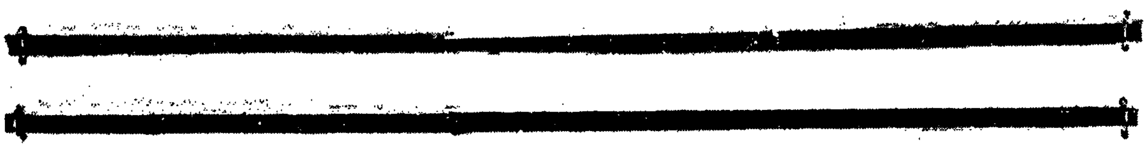
VELOCITY = 160 FT/SEC

PRESSURE = 1800 PSIA

$T_{WALL\ MAX}$ = 732°F

ϕ_{MAX} = 10.4 BTU/IN^2-SEC

PROPANE GRADE: NATURAL



TEST: HTB6-797-112

VELOCITY = 50 FT/SEC

PRESSURE = 1800 PSIA

$T_{WALL\ MAX}$ = 1164°F

ϕ_{MAX} = 6.20 BTU/IN^2-SEC

PROPANE GRADE: INSTRUMENT

Figure 23. Test Sections - Coking Series

8. Propane Purity

Two grades of propane were purchased for this program - natural and instrument grade. Nine cylinders (20 gallons each) of natural grade have been used. Five of the nine were purchased from Matheson and the remainder from Liquid Carbonics.

The initial run tank fill consisted of 5 Matheson and 2 Liquid Carbonics cylinders. An additional cylinder was added on 16 April 1980. A sample of the run tank contents was taken on 23 May 1980 after completion of heat transfer test #107. Propane purity was near nominal, 95.4%.

Prior to initiating heat transfer Test #108, an additional cylinder was added, and Tests 108 through 111 were completed. On 1 July 1980, a sample was again taken prior to purging the system for addition of instrument grade.

The analysis showed an unusually low propane content, 87%, while ethylene and butane components were each up to 5%.

On 18 July 1980, following Test #112, the run tank and unused cylinders of product were sampled.

Sample results are tabulated on Table XIII.

D. TASK III - PRELIMINARY ENGINE SYSTEM CHARACTERIZATION

1. Objective

The objective of Task III was to characterize engine LOX/hydrocarbon system parameters, in particular performance and weight for LOX/hydrocarbon orbit maneuvering and reaction control system thrusters.

The Task III results formed a basis for a related contract, LOX/Hydrocarbon Auxiliary Propulsion System Study (Ref. 4) conducted by McDonnell Douglas Astronautics Company to characterize the engine pod system. ALRC also supported this program under subcontract, to provide additional parametric data.

2. Scope

Task III was conducted in two phases. "Baseline" engine point designs were evaluated in the initial phase and "parametric" engine point designs in the following phase.

Thirty-eight OME and twenty RCE design points were analyzed on the two contracts. Of the OME design points, twenty-eight were pump-fed systems and ten were pressure-fed. The pump-fed systems were primarily gas generator

TABLE XIII

PROPANE SAMPLE ANALYSIS

Sample	Component, Volume %				
	Ethane	Ethylene[1]	Propane	Butane	Unknown[2]
23 May 1980 (Run Tank)	1.32	-	95.4	3.03	0.25
1 July 1980 (Run Tank)	0.56	5.14	87.36	5.48	1.46
18 July 1980 (Run Tank)	0.10		99.00	0.42	0.48
Liquid Carbonic Instrument Grade, as received	0.04		99.95		0.01
Liquid Carbonic Natural Grade, as received	1.08	5.23	90.85	2.82	0.02

1 Tentative assignment; retention time is consistent.

2 Peak shape is similar to butane. One speculative assignment is butylene, but no standards were available.

cycles in which fuel-rich gas was used to drive separate turbopumps for the two propellants; common shaft concepts were also investigated. Several expander cycle design points were evaluated. All twenty of the RCE designs were treated as pressure-fed; chamber pressures were in some cases sufficiently high to require pump feed systems, however, and these were evaluated in the Reference 4 study assuming an OME turbopump could service multiple RCE thrusters. Twelve vernier engine design points were also analyzed in a cursory manner.

3. Results and Conclusions

In general, methane and propane were found to offer the highest performance, with methane being slightly higher than propane. Pump-fed systems had higher performance than pressure-fed concepts, by virtue of higher chamber pressure and higher area ratio within the constraint of a fixed nozzle exit diameter. Pressure-fed engine performance with ammonia and ethyl alcohol was not significantly better than that of the current engine which uses storable propellants. Pump-fed engines using methane or propane offered a 50 sec Isp improvement, however. Performance trends for the RCE thruster design points were similar for the four fuels.

Engine weights varied inversely with chamber pressure for the pressure-fed OME designs; only one thrust level was addressed. Pump-fed engine weights varied directly with thrust and only slightly with chamber pressure. Weights did not vary significantly with fuel selection in either case.

Key results for all design points analyzed under both this and the McDonnell-Douglas contract are given in Table XIV.

4. Approach

The analytical approach for a given design point was to first calculate the chamber coolant needs, which determined the turbopump requirements or tank pressures in the pressure-fed engine concepts. The turbopump requirements in turn dictated the gas generator requirements. The three components were thus analyzed sequentially. Thereafter the overall engine performance and weight figures could be defined.

As in Task I, the SCALER or BOSCALE computer programs were used for the regenerative cooling analyses. The turbomachinery was analyzed with the TURBO computer program written by ALRC.

The film-coolant requirements for the RCE and vernier thrusters were calculated by means of the HOCOOL computer program written by ALRC. This program is based on an entrainment model in which the core gas is assumed to be

TABLE XIV

LOX/HYDROCARBON APS PARAMETRIC STUDIES - KEY RESULTS

PRESSURE-FED OME (F_v = 6K lbF)

PROPELLANTS	Pc, Psia	CHAMBER MAT'L	TCA MR	TCA Isp_v, Sec	%FFC	INTERFACE PRESS: OX/F	ENGINE* WEIGHT	COMMENTS
LOX/C_3H_8 (NASA)	100	Zr-Cu	1.92	324.3	30 (10.3)**	143/183	323.1	LIQUID REGEN
	100	Zr-Cu	2.75	337.0	Ø	143/157	322.1	AMBIENT C_3H_8 VAPOR REGEN
	100	Ni	2.75	337.0	Ø	143/161	318.0	AMBIENT C_3H_8 VAPOR REGEN
	150	Zr-Cu	1.79	326.7	35 (12.5)	209/381	285.8	LIQUID REGEN
LOX/CH_4 (NASA)	100	Zr-Cu	3.00	343.2	Ø	143/147	318.0	VAPOR REGEN
	100	Ni	3.00	343.2	Ø	143/150	318.0	" "
	150	Zr-Cu	3.40	346.2	Ø	209/231	289.4	" "
LOX/NH_3 (NASA)	100	CRES	1.25	318.8	11 (4.9)	143/159	317.7	LIQUID REGEN
LOX/C_2H_5OH (MDAC)	100	Zr-Cu	1.60	319.9	Ø	143/206	313.7	" "
	150	Zr-Cu	1.60	326.4	Ø	209/467	286.1	" " 2 PASS REGEN

*VAPOR REGEN ENGINE WGTS DO NOT INCLUDE ALLOWANCE FOR POTENTIAL HEAT EXCHANGER NOZZLE EXTENSION
**%FFC OF TOTAL ENGINE FLOW

TABLE XIV (CONT.)

● PUMP-FED OME

PROPELLANTS	F_v/Pc	CHAMBER MAT'L	ENGINE MR	ENGINE Isp_v	%FFC	PUMP DISCHARGE PRESSURE: OX/FUEL	ENGINE WEIGHT	COMMENTS
LOX/C_3H_8 (NASA)	6K/400	Ni	2.58	354.9	3 (0.8)*	535/980**	328.3	NOM Cg
	"	Ni	2.66	355.3	Ø	535/980	328.3	FLAT Cg
	"	CRES	2.02	343.3	25 (7.9)	535/980	325.3	
	6K/800	Zr-Cu	2.81	368.7	Ø	1020/1196	327.9	
	10K/400	"	2.69	351.7	Ø	535/980	393.4	
	10K/800	"	2.83	364.2	Ø	1040/1155	395.6	W/O BOOST PUMPS
	"	"	2.82	363.8	Ø	1040/1155	408.5	WITH BOOST PUMPS
LOX/CH_4	6K/400 (NASA)	Ni	3.41	360.8	Ø	535/1080	326.9	
	" (MDAC)	Ni	3.50	363.7	Ø	535/1150	317.2	EXPANDER CYCLE
	" (MDAC)	Zr-Cu	3.50	363.7	Ø	535/1150	317.2	EXPANDER CYCLE
	6K/600 (MDAC)	Ni			NOT FEASIBLE			EXPANDER CYCLE
	" (MDAC)	Zr-Cu			NOT FEASIBLE			EXPANDER CYCLE
	6K/800 (MDAC)	Ni			NOT FEASIBLE			EXPANDER CYCLE
	" (MDAC)	Zr-Cu			NOT FEASIBLE			EXPANDER CYCLE
	10K/400 (NASA)	Zr-Cu	3.44	356.0	Ø	535/980	382.4	
	10K/800 (NASA)	Zr-Cu	3.43	366.0	Ø	1040/1123	382.6	FUEL REGEN
	" (NASA)	"	3.39	365.3	Ø	1308/1020	382.1	OXID REGEN
	" (NASA)	"			NOT FEASIBLE			EXPANDER CYCLE
LOX/NH_3 (NASA)	10K/400	CRES	1.21	326.5	13 (5.8)	533/614	376.8	
	10K/800	"	0.93	317.4	33 (17)	1040/1330	383.8	
LOX/C_2H_5OH (MDAC)	6K/400	Ni	1.59	334.4	10 (3.8)	535/1094	329.7	NO SOOT DEPOSITION
	"	Zr-Cu	1.77	339.6	Ø	535/1036	"	"
	6K/600	Ni	1.33	324.2	25 (10.6)	770/1084	325.4	"
	"	Zr-Cu	1.76	346.1	Ø	770/1066	"	"
	6K/800	Ni	1.24	318.7	30 (13.3)	1020/1128	323.9	"
	"	Zr-Cu	1.72	346.3	2 (0.7)	1020/1150	"	"
	10K/400	Zr-Cu	1.77	335.5	Ø	555/1121	404.1	2 PASS REGEN
	10K/800	"	1.75	344.1	Ø	1040/1338	389.4	

*%FFC OF TOTAL ENGINE FLOW

**ALL C_3H_8 & CH_4 DESIGNS HAVE SUPERCRITICAL REGEN COOLING

TABLE XIV (CONT.)

550-LBF AND 870-LBF RCE

PROPELLANTS	Fv/Pc	PROP. INLET* STATE: OX/F	MR	I_{sp_V}	% FFC	PROP. INLET PRESSURE: OX/F	TCA WGT
LOX/C_3H_8 (NASA)	870/100	L/L	2.24	297.9	18.6 (5.7)	177	23.1
	870/150	L/L	2.23	305.4	19 (5.9)	256	22.0
	870/150	G/L	2.23	305.6	18.8 (5.8)	202/256	22.9
	870/250	G/L	2.20	315.5	20 (6.3)	316/414	21.8
	870/300	L/L	2.19	318.8	20.5 (6.4)	492	20.6
LOX/CH_4	870/100 (MDAC)	L/L	2.49	302.8	17.1 (4.9)	177	23.1
	870/150 (NASA)	L/L	2.49	313.7	17 (4.9)	256	22.0
	870/150 (NASA)	G/G	2.48	313.9	17.2 (5.0)	204	24.8
	870/250 (MDAC)	L/L	2.47	318.8	17.6 (5.1)	420	20.9
	870/250 (NASA)	G/G	2.43	322.2	19 (5.5)	316	23.7
	870/400 (MDAC)	L/L	2.69	326.7	20.8 (5.6)	659	20.1
LOX/NH_3 (NASA)	870/150	L/L	1.12	292.4	20 (9.4)	246	21.8
	870/250	G/L	1.12	301.6	20 (9.4)	316/398	21.5
LOX/C_2H_5OH (MDAC)	870/150	L/L	1.30	288.3	18.9 (8.2)	252	21.8
	550/100	G/L	1.29	281.5	19.4 (8.5)	143/173	21.8
	550/250	G/L	1.40	300.0	22.5 (9.4)	326/403	20.0
	550/400	G/L	1.39	308.0	22.7 (9.5)	508/632	19.4
	870/100	G/L	1.30	275.8	18.7 (8.1)	143/173	23.7
	870/250	G/L	1.40	294.5	22.2 (9.2)	326/403	21.5
	870/400	G/L	1.40	303.6	22.3 (9.3)	508/632	20.7

*USED FOR INTERFACE PRESSURE CALCULATIONS. PERFORMANCE ANALYSES ARE BASED ON NBP PROPELLANT TEMPERATURES AND THERMAL ANALYSES ON FILM COOLANT INJECTED AS A SATURATED VAPOR.

TABLE XIV (CONT.)

25-LBF RCE

PROPELLANTS	Pc, PSIA	PROP. INLET STATE: OX/F	MR	I_{sp_V}	% FFC	PROP. INLET PRESSURE: OX/F	TCA WGT
LOX/C_3H_8 (NASA)	100	L/L	2.75	223.4	23	SAME AS 870-LBF RCES	8 ± 1 LBM
	150	L/L	"	229.0	"		
	150	G/L	"	229.2	"		
	250	G/L	"	236.6	"		
	300	L/L	"	239.1	"		
LOX/CH_4 (NASA)	150	L/L	3.00	235.3	21		
	150	G/G	"	235.4	"		
	250	G/G	"	241.6	"		
LOX/NH_3 (NASA)	150	L/L	1.4	219.3	39		
	250	G/L	"	226.2	"		
LOX/C_2H_5OH (MDAC)	150	L/L	1.6	216.2	36		
	250	G/L	1.8	225.8	33		

entrained by the film coolant gas in an annular mixing layer along the chamber periphery. It incorporates the framework for regenerative cooling analysis. The program was also used to determine the film coolant requirements for the OME thrusters.

5. Groundrules and Assumptions

Groundrules and assumptions which guided the design point analyses of the OME, RCE, and vernier thrusters are identified in Table XV, along with the rationale for selection and the impact on the engine design.

It should be noted specifically that the regenerative cooling analysis was updated for the empirical heat transfer correlation developed in Task I for propane; this correlation was used for both propane and methane in the design point studies. Also, the gas-side heat transfer correlating coefficient (Cg) profile was changed from the Task I parametric studies to reflect the experimental results since obtained by ALRC in hot fire testing with LOX/RP-1 under contract NAS 3-21030, High Density Fuel Combustion and Cooling Investigation Reference 12.). Figure 24 shows the much higher cg profiles used for both low chamber pressure (contraction ratio CR = 2) and high chamber pressure (contraction ratio CR = 3.3) cases in comparison to the "standard" profile used in Task I.

6. Technical Discussion

Engine cycles analyzed for the OME system are shown on Figure 25. The RCE was treated as a simple pressure-fed engine similar to the pressure-fed OME, except that the thrust chamber is film-cooled.

Data sheets summarizing the pressure schedule, thrust chamber thermal analysis, turbopump and gas generator analysis, performance, and weights analyses are given in Table XVI for all baseline engine design points, and in Table XVII for all parametric design points, analyzed under the NASA contract.

TABLE XV

GROUND RULES AND EVALUATION CRITERIA FOR OME ANALYSIS

GROUND RULES AND EVALUATION CRITERIA FOR OME ANALYSIS		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
The following ground rules and evaluation criteria are proposed for the analysis of the OME systems.			
A. Propellants, Propellant Storage Condition, Engine Operating Point			
1. Propellants, engine thrust and chamber pressure, propellant storage temperature.	1. Per Statement of Work and reiterated on Table I.	Specified by NASA-JSC.	—
2. Nominal operating point mixture ratio.	2. Optimum kinetic performance of core gases, additional film cooling as required.	Specified by NASA-JSC. Provides maximum Isp design.	—
3. Propellant storage pressure	3. Pressure-fed: as required by system pressure schedule; pump-fed: determined by turbopump requirements.	Specified by NASA-JSC.	—
B. Applicable Requirements of Procurement Specification (MC621-0009)			
1. Para 3.1.2 Interface Definition Para 3.1.2.1 Envelope	1. Will not exceed nozzle skirt envelope; forward envelope to accommodate required components.	Specified by NASA-JSC. Makes basic operational requirements the same as the existing OMS engine.	—
2. Para. 3.2.1.1 Life Requirements Para. 3.2.1.1.1 Operating Life Para. 3.2.1.1.2 Useful Life Para. 3.2.1.1.3 Shelf Life	2. 100 missions ten years, .00 missions ten years		
3. Para 3.2.1.8.1 Mission Profile	3. Thirty-day mission.		

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XV (cont.)

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
4. Para. 3.2.1.8.2 Engine Start Capability	4. 500 starts, times scatter factor of 4 per Para. 3.2.2.3.3 Fatigue		
5. Para. 3.2.1.8.3 Minimum Engine Firing Time	5. 2 seconds		
6. Para. 3.2.1.8.4 Minimum Engine Off Time	6. 240 seconds		
7. Para. 3.2.1.8.5 Maximum Duration Firing	7. No design limit		
8. Para. 3.2.1.8.6 Engine Duration Capability.	8. 15 hours		
9. Para. 3.2.2.11.2 Chamber Cooling	9. 500 °F maximum exterior, no refractories or ablatives.		
10. Para. 3.2.2.12.1 Nozzle Cooling	10. Radiation cooling		
11. Para 3.2.2.14 Propellant Valve Assembly	11. 500 dry/5000 wet cycles		
C. Component Design Considerations			
1. Engine components: Thrust chamber assembly:	1. Per Statement of Work: chamber, nozzle, injector, igniter, valves	Specified by NASA-JSC.	
Turbopump Assembly:	Main pump, turbine, gas generator, exhaust nozzle; boost pump & drive in some concepts		
Other:	Gimbal system; instrumentation; controls.		

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XV (cont.)

ORIGINAL PAGE IS OF POOR QUALITY

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
2. Engine cycles	2. (a) ... (b) ... -driven turbopump: ... nly fuel-rich ... will investigate ... te and combined ... shaft; for separate ... ider turbines in ... iven boost pump ... cycle (methane only)	Specified by NASA-JSC.	—
3. Chamber Cooling	3. Up-pass and two-pass regenerative, with film cooling as required.	Specified by NASA-JSC	—
B. Analytical Bases Thrust Chamber Cooling Analysis 1. General approach	1. Design for most severe O/F; indicated O/F variation is ± 20% pressure-fed, ± 5% pump-fed.	Specified by NASA-JSC	Wider operating Pc and MR ranges have a general tendency to drive the engine to a conservative desig at the nominal operating point. Hence, nominal engine performance and weight is compromized.
2. Gas-side heat transfer	2. Turbulent correlation; Cg profile from LOX/RP-1 Program (NAS 3-21030).	Data is judged to be the best available.	If the RP-1 profile is not the same for C_3H_8, CH_4 or NH_3 the calculated film coolant flow rates and ΔPc.j. are not valid.
3. Coolant heat transfer	3. Propane, methane convection and boiling: empirical correlations developed previously in NAS 9-15958; ammonia: convection: Sieder-Tate; boiling: JPL/RMI data. C_2H_5OH: Convection: Hines	Data is judged to be the best available	Propane and methane correlations should be excellent. Validity of NH_3 coefficients should be good. NOTE: The thermal characteristics for the pressure-fed LO_2/C_3H_8 and LO_2/NH_3 point designs were controlled by the burnout heat flux limitation.
4. Burnout Safety Factor (BOSF)	4. BOSF = 1.3 for propane, methane-based on NAS 9-15958 data scatter, BOSF= 1.67 for ammonia-based on JPL/RMI data scatter. C2H5OH BOSF=1.3*	Data is judged to be the best available.	
5. Gaseous coolant Mach number	5. 0.3 maximum.	Good design practice	—
6. Coolant-side wall temperature.	6. Consistent with cycle life, creep, and carbon deposition considerations: 800°F max. for propane, based on coking 1000°F max. for methane in Zr-Cu, based on cycle life and creep; 800°F max. for ammonia in 304L, based on cycle life. C_2H_5OH 800°F max. based on coking.	Date is judged to be the best available.	Will make results conservative or optimistic depending on the validity of these values. NOTE: The thermal characteristics for the pump-fed point designs for LO_2/C_3H_8 and LO_2/CH_4 were controlled by the coolant-side wall temperature limitation.

*AF Report No: FTD-MT-24-146-68 Translation Soviet Data, 1964

C-2

TABLE XV (cont.)

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
7. Gas-side wall temperature.	7. Consistent with cycle life and creep consideration: 1000°F for Zr-Cu, 800°F for 304L.	Data is judged to be the best available.	Will make results conservative or optimistic depending on the validity of these values. NOTE: The thermal characteristics for the pump-fed point design for LO_2/NH_3 was controlled by the gas-side wall temperature limitation.
8. Coking on gas-side	8. Consider in overall bulk temperature rise but not local heat balance; factor: 0.42 for propane. 0.765 for methane. 0.5 for C_2H_5OH	This is a conservative approach that considers gas-side coking of walls is not immediate following initial engine start. Factors are based on results of previous studies.	Will make results conservative or optimistic depending on the validity of these values. Using higher factors would require additional film cooling for the pressure-fed LO_2/C_3H_8 point design; i.e., these coking factors favor LO_2/C_3H_8 concepts.
9. Channel configuration	9. Consistent with life requirements and fabricability; maximum depth-to-width ratio: 5 Minimum channel width: 0.0325 inch Minimum depth: 0.030 inch Minimum land width: .0325 inch	Based on current manufacturing limitations/capabilities without special processing.	Increased capability would decrease film coolant requirements of pressure-fed cases.
Performance Analysis			
1. Chamber contour	1. Not to exceed current exit diamete envelope; barrel and throat area scaled in proportion to thrust/chamber pressure.	Eliminates potential for redesigning Orbiter and/or Pod structure/aerodynamic surfaces.	Limits nozzle area ratio and biases results in favor of pump-fed concepts.
2. Performance prediction	2. Simplified JANNAF methodology	Provides good results for time and resources expended.	Performance comparisons are valid
3. Energy release efficiency	3. Same as current ONE	State-of-the-art, precludes costly development programs.	—
4. Injector pressure drop	4. Consistent with chugging considerations.	Engine design parameter that must be considered.	—
5. Igniter design	5. Based on recent ALRC LOX/HC technology.	Data is judged to be the best available	No impact as the affect of igniters on system evaluation is essentially nil.

TABLE XV (cont.)

Turbopump Assembly Analysis

1. Pump Design Limits

	Oxygen	Ammonia	Methane	Propane	Ethyl Alcohol	SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
• Suction specific speed - maximum design value RPM GPM1/2/FT3/4	30,000	36,000	37,500	30,000	30,000	ALRC estimated state-of-the-art criteria derived from LO_2/LH_2 experience.	Based on results completed at this time, the TPA criteria has not resulted in any significant compromise in TPA designs.
• Thermodynamic suppression head - minimum design feet of liquid	3.5	6.6	7.1	3.5	[illegible]		
• Suction inlet velocity maximum design coefficient $2g\ NPSH/C_m^2$ (typical design criteria)	2.3	1.67	1.58	2.29	2.3		
• Minimum impeller diameter - inch		0.7					
• Minimum impeller exit blade width - inch		0.03					
• Minimum inducer inlet blade flow coefficient - fluid axial velocity/blade tangential velocity		0.06					

2. Turbine Design Limits

	Oxygen	Ammonia	Methane	Propane	Ethyl Alcohol
• Minimum blade height-to-hub ratio blade height/hub diameter		0.05			
• Minimum blade height - inch		0.15			
• Minimum rotor hub-to-blade tip ratio		0.6			
• Minimum rotor diameter - inch		1.0			

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XV (cont.)

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
3. Turbine Stress Design Criteria		ALRC estimated state-of-the-art criteria derived from LO_2/LH_2 experience.	Based on results completed at this time, the TPA criteria has not resulted in any significant compromise in TPA designs.
• Mean blade root centrifugal stress	Based on modified Goodman diagram relating alternating stress to steady-state stress.		
• Design allowable blade root stress	Assumes 20% overspeed, 5% centrifugal bending, 10% gas bending stress		

4. Bearing Design Limits

	Oxygen	Ammonia	Methane	Propane	Ethyl Alcohol
• Bearing DN limit - ID innerface in mm times speed in RPM x 10^{-6}	1.5	1.6	1.9	1.6	1.5
• Bearing size	15 to 40 mm				

5. Face Seal Design Limits

	Oxygen	Ammonia	Methane	Propane
• Face contact seal maximum fluid pressure differential times rubbing velocity (psig x ft/sec)	50,000	120,000	120,000	120,000

6. Turbopump efficiency, size, weight

• Efficiency	Empirical correlations
• Size, weight	Empirical correlations

TABLE XV (cont.)

			SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
Instrumentation, Valves, and Controls Analysis				
1. Design approach	1.	Use current ONE and Titan engine as basis.	Precludes costly and lengthy development programs	—
Engine Weight and Volume Analysis				
1. Component:				
Thrust chamber assembly		Scaled from current ONE (will include redundant features)	Best data available	—
Turbopump assembly		Calculated separately	—	
G.mbal system		scaled from current ONE	Best data available	—

TABLE XV (cont.)

GROUND RULES AND EVALUATION CRITERIA FOR RCE ANALYSIS		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
The following ground rules and evaluation criteria are proposed for the analysis of the RCE systems.			
A. Propellants, Propellant Storage Condition, Engine Operating Point			
1. Propellants, engine thrust and chamber pressure, propellant storage temperature	1. Per Statement of Work and reiterated in Table II.	Specified by NASA-JSC	—
2. Nominal operating point mixture ratio.	2. Optimum kinetic performance of core gases, additional film cooling.	Specified by NASA-JSC. Provides maximum Isp design.	—
3. Propellant storage pressure.	3. Pressure-fed: as required by system pressure schedule; pump-fed (to accumulators): determined by turbopump requirements.	Specified by NASA-JSC	—
B. Applicable Requirements of Procurement Specification (MC647-0028, 29)			
1. Para. 3.1.1 Interface Definition Para. 3.1.1.1 Envelope	1. Chamber and nozzle envelope maintained, turbopump assembly envelope to be determined; accumulator configuration not addressed.	Specified by NASA-JSC. Makes basic operational requirements the same as the existing OMS engine.	—
2. Para 3.2.1.1 Life Reqmts. Para 3.2.1.1.1 Operating Life Para 3.2.1.1.3 Shelf Life	2. 50,000 cycles (vernier: 500,000) 20,000 seconds duration (vernier: 125,000) 10 years.		
3. Para 3.2.1.2.1 Nominal Duty Cycle	3. Steady-state duration 800 sec (vernier: 125) pulse widths from 0.080 to 0.960 seconds; minimum off-time 0.080 seconds; mission duty cycle less than 350 seconds or 1000 starts; mission duration		

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XV (cont.)

			SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
		7 days with design objective of 30 days.	Specified by NASA-JSC. Makes basic operational requirements the same as the existing OMS engine.	
4.	Para 3.2.1.4.6 Impulse Bit	4. 50 lbs-sec for 0.080 sec firing (vernier: 1.3 lb-sec)		
5.	Para 3.2.1.4.7.3 External Surfaces	5. Maximum external temperatures indicated, typically 500°F at forward end, 2200°F at aft end.		
C.	Component Design Considerations			
1.	Engine components: Thrust chamber assembly Turbopump assembly	1. Per Statement of Work: chamber, nozzle, igniter, valves pump and tur[illegible]; flow corresponding to [illegible]0-10,000 lbf thrust with discharge pressures of 400-1200 psia	Specified by NASA-JSC	
	Propellant conditioning assembly	Heat exchanger, gas generator, exhaust nozzle		
	Other	Low thrust (25 lbF) vernier engine		
2.	Engine cycles	2. (a) Pressure-fed (b) Gas-generator-driven turbopump with accumulator tanks	Specified by NASA-JSC	
3.	Chamber Cooling	3. [illegible]cted and non-ducted film cooling	Specified by NASA-JSC	All 870-lbf thrusters were assumed to be non-ducted film cooling because for the existing RCE chamber configuration ducted film cooling advantage was not considered significant because of the short barrel length.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XV (cont.)

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
D. Analytical Bases			
Thrust Chamber Cooling Analysis			
1. General approach	1. Design for most severe point in operating point box; indicated Pc and O/F variation ± 40% about nominal	Specified by NASA-JSC	Large variation in operating parameters results in relatively large TCA inlet pressures.
2. Film coolant temperature profile	2. Based on mixing model correlated with empirical data	Best approach available.	—
3. Wall temperature	3. Consistent with current engine: 2400°F Maximum, to meet cycle life and exterior temperature requirements.	Specified by NASA-JSC	—
Performance Analysis			
1. Chamber contour	1. Not to exceed current exit diameter envelope; barrel and throat area scaled in proportion to 1/chamber pressure.	Precludes re-packaging/locating of RCE.	Limits nozzle area ratio
2. Performance prediction	2. Simplified JANNAF methodology	Provides good results for time and resources expended	Performance comparisons are valid
3. Energy release efficiency	3. Same as current RCE	State-of-the art, precludes costly development programs.	—
4. Injector pressure drop	4. Consistent with chugging considerations.	Engine design parameter that must be considered	—

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XV (cont.)

		SELECTION RATIONALE	IMPACT ON ENGINE DESIGN
Turbopump Assembly Analysis			
1. Design approach	1. Utilize applicable ONE configuration	Specified by NASA-JSC	—
Heat Exchanger Analysis			
1. Size, pressure drops	1. Standardized charts for tube in shell	Existing data is adequate since heat exchanger characteristics are minimal and will not influence selection of RCS main issues.	—
2. Weight	2. Simple calculation		
Vernier Thruster Analysis (vernier may double as igniter)			
1. Film coolant requirements	1. Calculate for one design, scale other in proportion to RCE requirements; base on recent ALRC LOX/HC igniter technology	A ROM approach to the 25-lbf thrusters is warranted since its characteristics are minimal and will not influence selection of RCS main issues.	—
2. Size, weight	2. Simple calculation		
Engine Weight and Volume Analysis			
1. Component:			
Thrust chamber assembly	Use current aft RCE as basis; adjust chamber and insulation weights for new contours.	Best data available	—
Turbopump assembly	Base on ONE configuration.		

OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

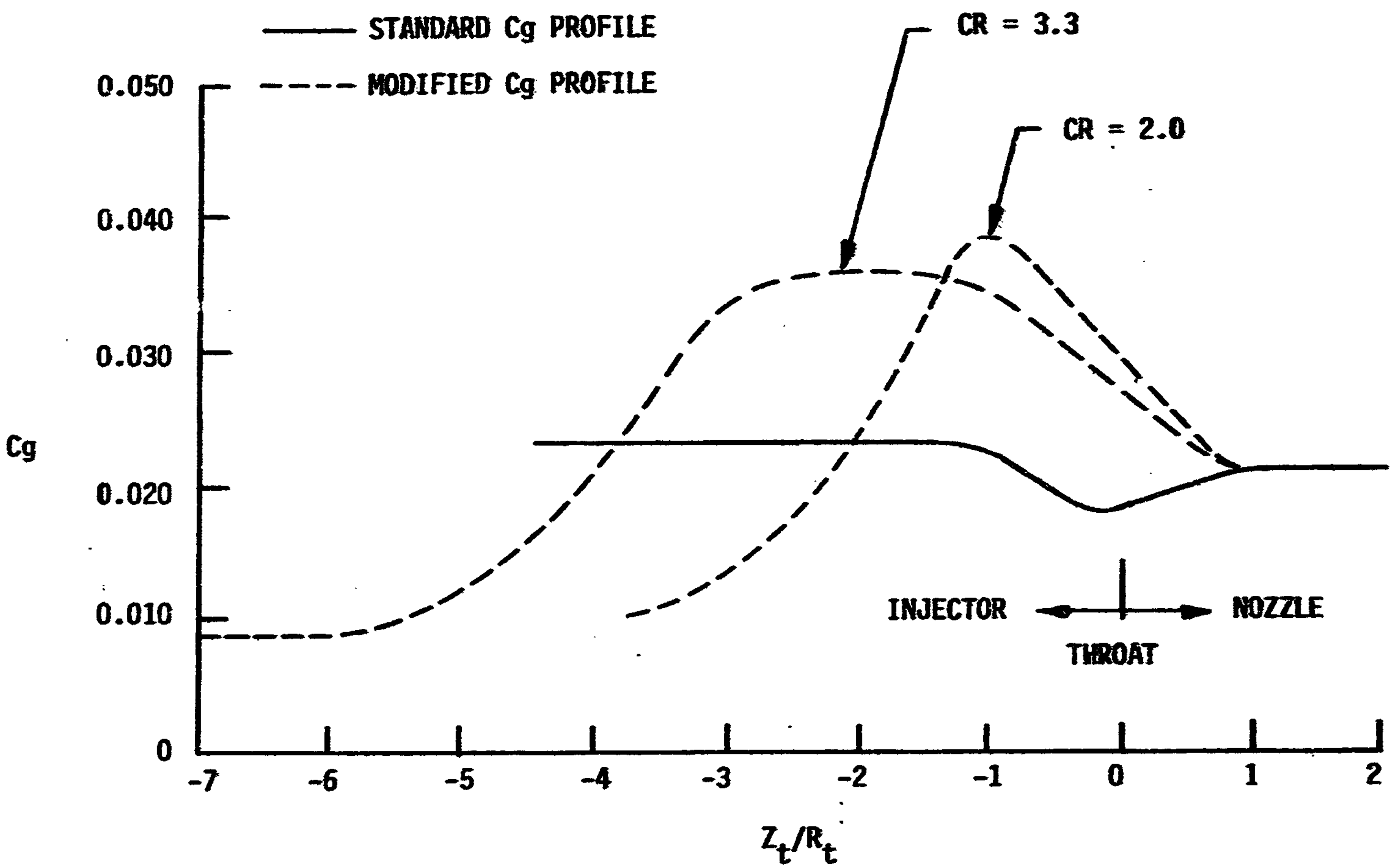


Figure 24. Standard and Modified Cg Profiles

ORIGINAL PAGE IS
OF POOR QUALITY

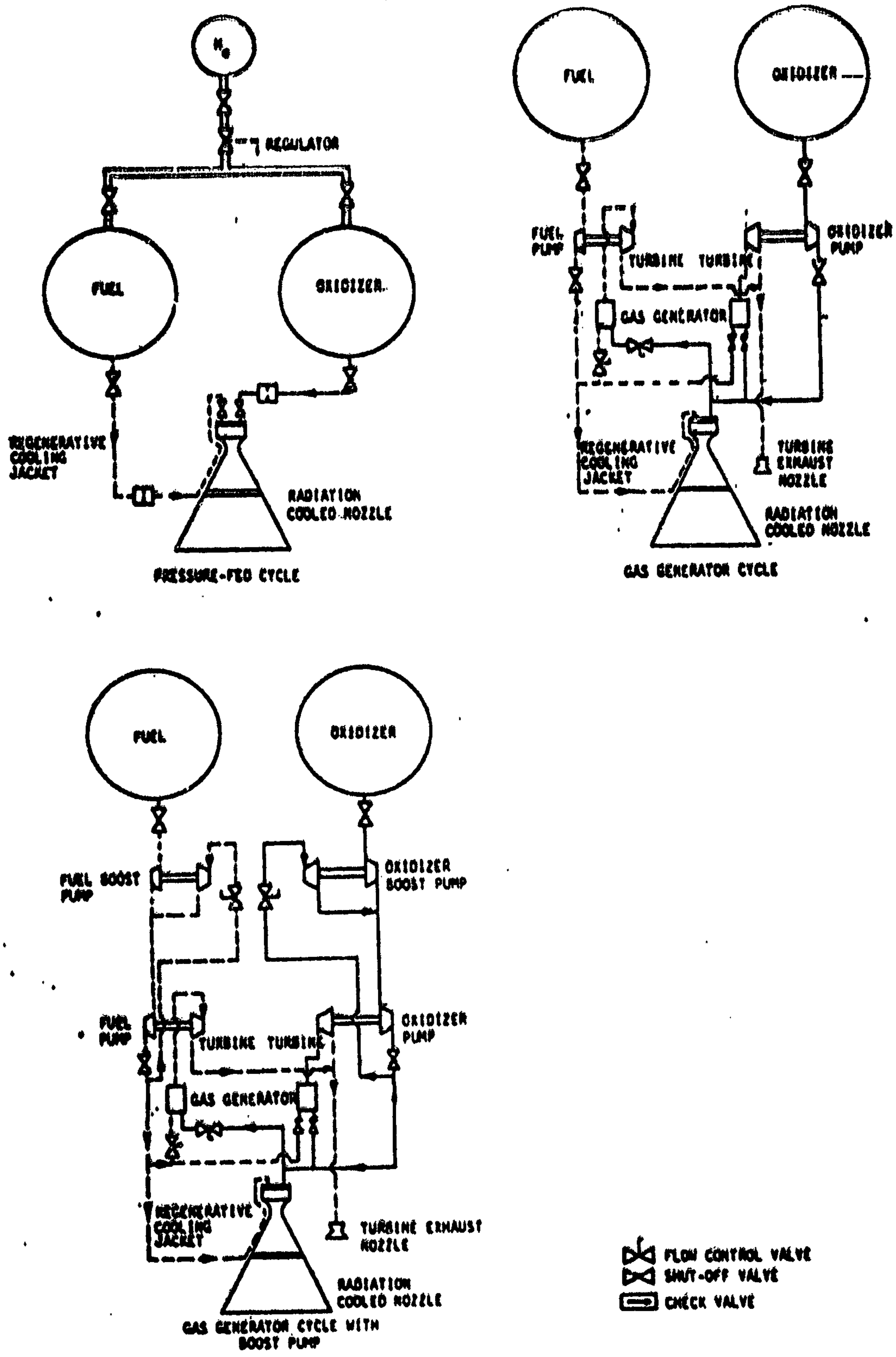


Figure 25. Candidate OME Cycles

TABLE XVI

BASELINE POINT DESIGN DATA DUMP

ORIGINAL PAGE IS
OF POOR QUALITY

3.0 PRESSURE SCHEDULE

3.1 OME Concept

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Boost Pump)	100/6K	800/10K	100/6K	800/10K	
• Plenum Pc, psia	100	800	800		800	100	800	
• Face Pc, psia	103	824	824		824	103	824	Based on A_c/A_t=3.3
• ΔPinj, psi*	35	160	160		160	35	160	Based on Chug Criteria
• ΔP_{TCV}, psi	8	20	20		20	5	20	Typical fo[illegible] t-ing [illegible]
• ΔP_{lines}, psi	-	16	16		16	-	16	[illegible]
• ΔP_{cj}, psi	40	115	115		188	16	290	
• ΣΔ P, psi	80	311	311		384	56	486	
• Interface or pump discharge pressure (ox/fuel), psia	143/183	1020/1135	1020/1135		1020/1208	143/159	1020/1310	
• ΔPinj/Pc	0.35	0.20	0.20		0.20	0.35	0.20	
• ΔP_{cj}/Pc	0.40	0.14	0.14		0.23	0.16	0.36	

NOTE: Pressure schedules for both OME and RCE engines are at the nominal operating Pc and MR.

*Pump-fed min. ΔPinj=0.2 x Pc

Pressure-fed ΔPinj:
- Liquid injection: min. ΔPi[illegible]/Pc=0.2
- Gas injection: min. ΔPinj/Pc=0.15

Note: Min. ΔPinj/Pc occurs at low Pc and high MR corner of operating box.

ORIGINAL PAGE IS
OF POOR QUALITY

3.2 RCE Concept

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• Plenum Pc, psia	150	250	150	250	150	250	
• Face Pc, psia	154	258	154	258	154	258	Based on Ac/At=3.3
• ΔPinj, psi* (ox/fuel)	82	38/136	82	38/38	72	38/120	Based on chug criteria
• ΔP_{TCV}, psi	20	20	20	20	20	20	Typical for existing engines.
• ΣΔP, psi	120	58/156	102	58/58	92	58/140	
• Interface Pressure, psia	256	316/414	256	316/316	246	316/398	
• ΔPinj/Pc (ox/fuel)	0.55	0.15/0.54	0.55	0.15/0.15	0.48	0.15/0.48	

Note: Pressure schedule is based on nominal operating Pc and MR

*Based on pressure-fed criteria (reference 3.1 OME concept).

ORIGINAL PAGE IS
OF POOR QUALITY

4.0 CHAMBER THERMAL ANALYSIS

4.1 OME Concepts

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Boost Pump)	100/6K	800/10K	100/6K	800/10K	
• Thrust, lbs	4400	9058	Same as design point w/o boost pump	Regenerative cooling with subcooled CH_4 is not feasible. Gaseous CH_4 will be examined in Phase II of study.	8867	4550	8905	
• Pc, psia	75	720			720	75	720	
• MR_{TCA}	2.31	3.15			3.68	1.495	1.13	
• MR_{Core}	3.3	3.15			3.68	1.68	1.47	
• $\dot{W}_{ox}$, lb/sec	9.62	18.84			18.79	8.66	14.52	
• $\dot{W}_f$, lb/sec	4.16	5.98			5.11	5.79	9.88	
• No.of Regen Passes	1 (up)	1 (up)			1 (up)	1 (up)	1 (up)	Counterflow
• ΔPc.j., psi	17	90			146	7	140	
• Pc.j.-in.psia	150	1080			1080	150	1080	
• Pc.j.out, psia	133	990			934	143	940	
• Tc.j.-in.°F	-44	-44			-259	-28	-28	
• Tc.j.-out* °F	28	186			-12	34	30	
• ΔTc.j.,°F	72	230			247	62	58	
• Regen ε	6.2	23.8			23.6	6.2	30.9	Radiation cooled nozzle attachment
• $\dot{W}_{ffc}$, lb/sec	1.25**	0			0	***0.64	***2.96	6% entrainment factor
• %Fuel Film Coolant	30	0			0	11	30	
• T_{ffc-in}, °F	28	-			-	-28	-28	
• Twg max, °F****	222[1]	835[1]			890[1]	440[2]	878[2]	1. 1000°F max 2. 800°F max.

NOTE: All thermal analyses were performed at low Pc and high MR corner of operating box. This is the most severe operating point.

*Bulk temperature of coolant is based on coked gas side wall: C_3H_8 $Q_{act}/Q = 0.42$
CH_4 $Q_{act}/Q = 0.765$

**Total fuel flow used for regenerative cooling.

***Fuel film cooling does not pass through regenerative coolant jacket.

****Twg is based on a carbon free wall surface.

ORIGINAL PAGE IS OF POOR QUALITY

4.0 CHAMBER THERMAL ANALYSIS (cont.)

4.1 OME Concepts (cont.)

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Boost Pump)	100/6K	800/10K	100/6K	800/10K	
• Tw_1 max	157[1]	796[1]			852[2]	152[1]	201[1]	1. 800°F max 2. 1000°F Max
• h_g*, BTU/in²-sec-°F	.00133	.00493			.00490	.00094	.00791	
• h_l*, BTU/in²-sec-°F	.00654	.0321			.0404	.0186	.0947	
• Tr*, °F	1510	5960			5840	2773	1728	
• Q/A_g max, BTU/in² sec	1.74	26.3			26.7	2.20	6.9	
• Q/A_l max, BTU/in² sec	1.02	16.9			14.6	2.32	7.5	
• $\frac{Q/A}{Q/A_{Bo}}$ max	0.77[1]	NA			NA	0.59[2]	0.54[2]	1. 0.77 max 2. 0.60 max
• Q Total, BTU/sec	160	868.8			1450	345	617	
• V_c max, ft/sec	38.3	136			242	28.1	180	
• V_c (Mach No)max	-	.044			0.234	-	-	0.3 max
• No of channels	350	145			143	328	144	
• Min Ch Depth, in	.038	.040			.036	.060	.041	
• ΔPc.j./Pc	0.23	0.12			0.13	0.09	0.19	
• Limiting Criteria	$\frac{Q/A}{Q/A_{Bo}}$	T_{wl}			T_{wg}-$T_{closeout}$	$\frac{Q/A}{Q/A_{Bo}}$	T_{wg}	

*@ max. flux.

4.2 RCE Concepts

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• 870 Lb Thrusters							
• Thrust, lbs	520	520	520	520	520	520	
• Pc, psia	90	150	90	150	90	150	
• MR_{TCA}	3.14	3.09	3.48	3.57	1.56	1.56	
• MR_{core}	3.85	3.85	4.20	4.41	1.96	1.96	
• $\dot{W}_{ox}$, lb/sec	1.386	1.335	1.[illegible]	1.361	1.123	1.088	
• $\dot{W}_f$, lb/sec	.442	.431	0.400	.381	.719	.697	
• $\dot{W}_{ffc}$, lb/sec	.082	.084	.069	.073	.147	.142	Saturated vapor at injection
• % Fuel Film Coolant (of $\dot{W}_f$)	19	20	17	19	20	20	6% entrainment factor
• Taw Max, °F	2400	2400	2400	2400	2400	2400	2400°F maximum
• % Fuel Film Cool. (of total flow)	4.5	4.8	3.9	4.2	8.0	8.0	
• 25 Lb Thrusters							Concept is similar to LO_2/RP-1 igniter which has duct film cooling. Core MR is 20:1 to reduce Twg. Selected overall MR is at Max. Isp.
• Thrust, lbs							
• Pc, psia							
• MR_{TCA}							
• MR_{core}							
• $\dot{W}_{ox}$, lb/sec							
• $\dot{W}_f$, lb/sec							
• $\dot{W}_{ffc}$, lb/sec							
• %Fuel Film Coolant							
• Taw Max, °F							

ORIGINAL PAGE IS OF POOR QUALITY

5.0 TPA AND GGA ANALYSIS

5.1 OME Concepts

PROPELLANTS	LOX/C_3H_8		LOX/CH_4	LOX/NH_3	COMMENTS
PUMPS	MAIN	MAIN + B/P	MAIN	MAIN	
• Pumps					
• $\dot{W}_{ox}$, lbm/sec	20.39	20.39/22.3*	20.84	15.84	
• $\dot{W}_f$, lbm/sec	6.80	6.8/7.3	5.96	14.98	
• $NPSP_{ox}$, psia	20.3	1.0/37	41	34	
• $NPSP_f$, psia	20.3	1.0/25	12.3	23	
• P_{iox}, psia	35	15.7/51	56	49	
• P_{if}, psia	35	15.7/39	27	38	
• P_{Dox}, psia	1040	51/1040	1040	1040	
• P_{Df}, psia	1155	39/1155	1123	1330	
• T_{sox}, °R	162.7	162.7	162.7	162.7	
• T_{sf}, °R	416.2	416.2	217	432	
• Spec. Spd_{ox}	1592	4157/1573	2870	2500	
• Spec SPd_f	1546	4157/1184	1293	1,870	
• Suct.Spec. Spd_{ox}	30,000	30K/20K	30,000	30,000	
• Suct.Spec Spd_f	30,000	30K/20K	34,750	35,770	
• No. of $Stages_{ox}$	1				
• No. of $Stages_f$	1				

*Boost Pump/Main Pump

NOTE: See page 3 of 3 for additional pump data

ORIGINAL PAGE IS
OF POOR QUALITY

5.0 TPA AND GGA ANALYSIS (cont.)

5.1 OME Concepts (cont.)

PROPELLANTS	LOX/C_3H_8		LOX/CH_4	LOX/NH_3	COMMENTS
PUMPS	MAIN	MAIN + B/P	MAIN	MAIN	
• Imp. D_{ox}, in	2.0	2.4/2.1*	1.26	1.23	
• Imp. D_f, in	1.38	1.8/1.8	1.63	1.62	
• η_{ox}, %	62.6	74/60.3	58.4	57.8	
• η_f, %	58.4	72/57	59.5	61	
• Turbines					
• Pin, psia	790	936/790	790	790	
• Pout, psia	79	88/79	79	79	
• Pr	10	-/10.0	10	10	
• $\dot{W}_{GG_{ox}}$, lbm/sec	0.42	.45	0.278	0.268	For ox TPA
• $\dot{W}_{GG_f}$, lbm/sec	0.28	.30	0.231	0.494	For fuel TPA
• T_{in}, °R	2000	-/2000	2000	2000	
• Tout, °R	1647	-/1624	1566	1539	
• ΔT, °R	353	-/376	434	461	
• Spec. Spd_{ox}	7.8	7.5	9.3	9.7	
• Spec Spd_f	12	9.6	10	14	
• No. of $Stages_{ox}$	1	1/1	1	1	
• No. of $Stages_f$	1	1/1	1	1	
• Tip D_{ox}, in	7.0	3.2/7.5	4.6	4.6	
• Tip D_f, in	4.0	2.4/5.1	3.9	4.3	
• η_f, %	67	51/62	64.6	68	
• η_{ox} %	62	46/64	64.0	64.3	

*Boost Pump/Main Pump

NOTE: See page 3 of 3 for additional turbine data

5.0 TPA AND GGA ANALYSIS (CONT.)

5.1 OME Concepts (cont.)

PROPELLANTS	LOX/C_3H_8		LOX/CH_4	LOX/NH_3	COMMENTS
PUMPS	MAIN	MAIN + B/P	MAIN	MAIN	
• Gas Generator					
• Pc_{GG}, psia	800	800	800	800	
• $\dot{W}_{GG_{ox}}$, lbm/sec	0.42	0.45	0.28	0.268	For Ox TPA
• $\dot{W}_{GG_f}$, lbm/sec	0.28	0.30	0.23	0.494	For fuel TPA
• MR	0.36	0.36	1.2	0.57	
• Cp, BTU/lbm-°F	0.64	0.64	0.78	0.59	
• γ	1.18	1.18	1.23	1.25	
• MW	20	20	13.5	16.6	
• Tc, °R	2000	2000	2000	2000	
• Additional Data					
Pumps					
• Oxid Flow, GPM	128.4	128.4/141*	131	100	
• Fuel Flow, GPM	84	84/90	101	158	
• Oxid Speed, RPM	45,630	9,470/42,700	74,550	74,900	
• Fuel Speed, RPM	90,800	14,420/67,000	87,250	80,000	
• Impeller Tip Spd.					
• Oxid, ft/sec	394	104/391	410	402	
• Fuel, ft/sec	549	121/529	623	567	
• Shaft Power					
• Oxid, HP	132	3.9 /144	133	103	
• Fuel, HP	93	1.8/100	112	202	
Turbine					
• Blade Tip Spd (u)					
• Oxid, ft/sec	1411	132/1400	1500	1500	
• Fuel, ft/sec	1576	153/1499	1500	1500	
• Ratio u/spouting velocity (u/v)					
• Oxid	0.32	0.32	0.29	0.32	
• Fuel	0.36	0.34	0.29	0.32	

*Boost Pump/Main Pump

6.0 PERFORMANCE ANALYSIS

6.1 OME Concepts

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Bst Pump)	100/6K	800/10K	100/6K	800/10K	
• Engine Fv, lbf	6000	10,099	10,106		10,084	6000	10,107	
• TCA Fv, lbf	6000	10,000	10,000		10,000	6000	10,000	
• Engine MR	1.92	2.82	2.81		3.43	1.25	.93	
• TCA MR	1.92	3.0	3.0		3.5	1.25	.94	
• Core MR	2.75	3.0	3.0		3.5	1.40	1.40	Max. ODK Isp MR
• Film Barrier MR	0.61	-	-		-	0.50	0.38	
• Turbine Ex. Fv, lbf	-	99	106		84	-	107	
• TCA $\dot{W}_{Tot}$, lbm/sec	18.50	27.06	27.06		27.03	18.82	31.08	
• TCA $\dot{W}_{ox}$, lbm/sec	12.16	20.30	20.30		21.03	10.46	15.06	
• TCA $\dot{W}_{f}$, lbm/sec	6.34	6.76	6.76		6.00	8.36	16.02	
• $\dot{W}_{turb}$, lbm/sec	-	0.70	0.75		0.51	-	0.76	
• % Fuel Film Coolant (of fuel flow)	30	0	0		0	11	33	
• Eng $\dot{W}_{ox}$, lbm/sec	12.16	20.49	20.50		21.31	10.46	15.34	
• Eng $\dot{W}_{f}$, lbm/sec	6.34	7.27	7.31		6.23	8.36	16.50	
• Eng Isp, Sec	324.3	363.8	363.4		366.1	318.8	317.4	
• TCA Isp, sec	324.3	369.5	369.5		369.9	318.8	321.7	
• Core Isp (ODK), sec	350.1	387.7	387.7		388.6	337.8	362.7	
• ISP_{turb}, sec	-	141.8	141.8		164.3	-	141.2	
• Ae/At	44	240	240		236	44	224	
• D_t, in.	6.48	2.78	2.78		2.80	6.48	2.95	
• D_e, in	43	43	43		43	43	43	
• % Fuel Film Coolant (of total flow)	10.3	-		-	-	4.9	17	
• Engine Total Flow Rate, lbm/sec	18.50	27.76	27.81		27.54	18.82	31.84	

TABLE XVI (cont.)

6.2 RCE Concept

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• 870 lbf Thrusters							
• TCA MR	2.23	2.20	2.49	2.43	1.12	1.12	
• Core MR	2.75	2.75	3.0	3.0	1.40	1.40	Max. ODK Isp MR
• TCA $\dot{W}_{ox}$, lbm/sec	1.97	1.90	1.98	1.91	1.57	1.52	
• TCA $\dot{W}_f$, lbm/sec	0.88	.86	.79	.79	1.40	1.36	
• %$\dot{W}_{ffc}$, (of fuel flow)	19 (5.9)*	20 (6.3)	17 (4.9)	19 (5.5)	20 (9.4)	20 (9.4)	
• TCA Isp, Sec	305.4	315.5	313.7	322.2	292.4	301.6	
• Core Isp(ODK), sec	399.7	351.7	347.1	358.1	327.3	337.0	
• Ae/At	27	46	27	46	25	46	
• D_t, in	2.04	1.56	2.02	1.56	2.06	1.56	
• D_{ex}, in	10.6	10.6	10.6	10.6	10.6	10.6	
• 25 lbf Thrusters							
• TCA MR	2.75	2.75	3.0	3.0	1.4	1.4	
• Core MR	20	20	20	20	20	20	
• TCA $\dot{W}_{ox}$, lbm/sec	.080	.077	.080	.078	.066	.064	
• TCA $\dot{W}_f$, lbm/sec	.029	.028	.027	.026	.047	.046	
• %$\dot{W}_{ffc}$, (of total flow)	23	23	21	21	39	39	
• TCA Isp, sec	229.0	236.6	235.3	241.6	219.3	226.2	
• Core Isp(ODK), sec	-	-	-	-	-	-	
• Ae/At	27	46	27	46	25	46	
• D_t, in	0.36	0.27	0.35	0.27	0.36	0.27	
• D_{ex}, in	1.80	1.80	1.80	1.80	1.80	1.80	

*Film cooling as % of total flow

OF POOR QUALITY

7.0 WEIGHT (LBM)

7.1 OME Concepts

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Boost Pump)	100/6K	800/10K	100/6K	800/10K	
• TCA (each)								
. Injector	20.4	8.4	8.4		8.5	20.1	9.5	
. Chamber	93.0	63.3	63.3		65.1	71.0	62.1	
. Nozzle	82.3	79.7	79.7		80.8	81.2	82.7	
. Controls+TCA Instr.	18.3	19.3	19.3		19.3	18.3	19.3	Does not include TCA Valve
	196.0	170.7	170.7		173.7	190.6	173.6	
• Thrust Structure Assy.	21.3	30.5	30.5		30.5	21.3	30.5	Scaled from OME
• Gimbal System	52.9	74.4	74.4		74.4	52.9	74.4	Scaled from OME
• Plumbing*	21.7	16.9	20.9		16.9	21.7	16.9	
• TPA (ox/fuel)*	-	24.7/5.7	28.6/11.1		7.6/6.0	-	7.5/7.3	
• Boost Pump(ox/fuel)*	-	-	7.3/3.3		-	-	-	
• GGA (ox/fuel)*	-	2.4/2.4	2.4/2.4		2.4/2.3	-	2.3/2.5	
• Controls & Instr								
. TCA Valve	21.0	21.0	21.0		21.0	21.0	21.0	
. Pneumatic Pack	7.6	7.6	7.6		7.6	7.6	7.6	
. Purge Valves	Ø	Ø	Ø		Ø	Ø	Ø	
. Instru*	2.6	9.6	9.6		9.6	2.6	9.6	
. GGA Valves*	-	7.8	7.8		7.8	-	7.8	
. TPA Controller*	-	22.8	25.0		22.8	-	22.8	
. Boost Pump* Circuit Valves	-	-	8.4		-	-	-	
	31.2	68.8	79.4		68.8	31.2	68.8	
Total, lbm	323.1	396.5	431.0		382.6	317.7	383.8	

*For two TPA's double these weights.

ORIGINAL PAGE IS
OF POOR QUALITY

7.2 RCE Concepts

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• 870-lbf Thruster							
• TCA (each)							
. Valves	2.5	3.4	2.5	5.3	2.3	3.1	
. Injector	5.3	4.2	5.3	4.2	5.3	4.2	
. Chamber/Nozzle	4.8	4.8	4.8	4.8	4.8	4.8	
. Insulation + Miscellaneous	9.4	9.4	9.4	9.4	9.4	9.4	
	22.0	21.8	22.0	23.7	21.8	21.5	
• Propellant Conditioning							
. Heat Exchanger (ox/fuel)	-	26.3/-	-	26.3/26.5	-	23.7/-	
. GGA(ox/fuel)	-	5.5/-	-	5.5/4.5	-	5.7/-	
		31.8		62.8		29.4	
• Controls & Instr							
. Pressure Reg. (ox/fuel)		6.2/2.0		6.2/6.2		6.2/2.0	
. Accumulator Valves (ox/fuel)		7.6/3.8		7.3/7.3		7.4/4.2	
. TPA GGA Valves		7.8		7.6		8.5	
. Prop.Cond GGA Valves		3.3		10.9		5.9	
. Main Propellant Valves(ox/fuel)		4.3/3.8		4.2/4.9		4.5/4.2	
. Instr.		14.4		19.2		14.4	
. TPA Controller		36.0		36.0		36.0	
		89.2		109.8		92.3	

7.2 RCE Concepts (continued)

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• 25-lbf Thruster							
TCA (each)	W_B	W_B+0.5	W_B	W_B+ 1.0	W_B	W_B+0.5	W_B is notation for the basic 25-lbf thruster weight which is 5-10 lbm. Deviations shown reflect valve weight differences

8.0 ENVELOPE/SIZE

8.1 OME Concepts

PROPELLANTS	LOX/C_3H_8			LOX/CH_4		LOX/NH_3		COMMENTS
Pc/F	100/6K	800/10K	800/10K (Boost Pump)	100/6K	800/10K	100/6K	800/10K	
• TCA (each)								Same as existing TCA (approx. 77" X 46")
. Length, in.	-	-	-	-	-	-	-	
. Nozzle Dia. in	-	-	-	-	-	-	-	
• TPA (ox/fuel)								
. Length, in.	-	5.6/5.0	5.2/5.0	-	3.6/4.2	-	3.6/3.8	
. Diameter, in.	-	7.5/4.4	6.0/4.4	-	4.8/4.6	-	4.8/4.4	
• GGA (ox/fuel)								
. Length, in.	-	10	10	-	10	-	10	
. Diameter, in	-	4	4	-	4	-	4	
• Boost Pump (ox/fuel)								
• Length, in.	-	-	5.2/5.6	-	-	-	-	
• Diameter, in.	-	-	4.4/3.6	-	-	-	-	

TABLE XVI (cont.)

8.2 RCE Concepts

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	150	250	150	250	
• 870 Lbf Thruster	-	-	-	-	-	-	Same as existing TCA's (approx.19" X 11")
• 25 Lbf Thruster	-	-	-	-	-	-	Same as existing TCA's (approx. 11" X 6")
• Heat Exchangers (ox/fuel)							
. Length, in	-	20	-	20/20	-	19	
. Diameter, in	-	12	-	12/11	-	11	
• GGA's (ox/fuel)							
. Length, in	-	11.0/-	-	11.0/11.0	-	11.0/-	
. Diameter, in.	-	5.1/-	-	5.1/4.3	-	5.4/-	

TABLE XVI (cont.)

9.0 HEAT EXCHANGER AND GGA ANALYSES

PROPELLANTS	LOX/C_3H_8		LOX/CH_4		LOX/NH_3		COMMENTS
Pc	150	250	250	250	150	250	
			Ox	Fuel			
• $\dot{W}_C$, lbm/sec		21	21	6		15	
• T_{C_i}, °R		162	162	200		162	
• T_{C_o}, °R		310	310	380		310	
• P_{C_i}, psia		900	900	900		900	
• P_{C_o}, psia		800	800	800		800	Judgment
• W_H, lbm/sec		3.4	2.9	1.6		2.7	
• T_{H_i}, °R		2,000	2,000	2,000		2,000	Fuel Rich GGA
• T_{H_o}, °R		800	800	800		800	Judgment
• P_{H_i}, psia		600	600	600		600	Judgment
• P_{H_o}, psia		300	300	300		300	Judgment
• ΔQ_C, Btu/sec		2,184	2,184	1,200		1,560	
• % η		80	80	80		80	Assumption
• $\dot{W}_H/\dot{W}_C$		0.16	0.14	0.27		0.18	

TABLE XVII

PARAMETRIC POINT DESIGN DATA DUMP

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XVII (cont.)

PRESSURE SCHEDULE - OME

PROPELLANTS	LO_2/C_3H_8				LO_2/CH_4		LO_2/NH_3	COMMENTS
Pc/F	100/6K	150/6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• Plenum Pc, psia	100	150	400	800	150	400	400	
• Face Pc, psia (ox/fuel)	103	154	412	824	154	412	412	Based on Ac/At = 3.3
• ΔP_{inj}, psi* (ox/fuel)	35/17	50	95	160	50/34	95	93	Based on chug criteria
• ΔP_{TCV}, psi	5	5	20	20	5	20	20	Typical for exist. engines
• ΔP_{lines}, psi	-	-	8	16	-	8	8	2% of Pc
• ΔP_{cj}, psi	32**	172	417***	176	38**	417***	81	
• $\Sigma\Delta$ P, psi	40/54	55/227	123/568	196/372	55/77	123/568	121/202	
• Interface or pump discharge pressure (ox/fuel) psia	143/157	209/381	535/980	1020/1196	209/231	535/980	533/614	
• $\Delta P_{inj}/Pc$	.35/.17	0.33	0.24	0.20	.33/.23	0.24	0.23	
• $\Delta P_{cj}/Pc$	0.32	1.15	.03	0.22	0.25	.03	0.20	

NOTE: Pressure schedules for both OME and RCE engines ~~are~~ at the nominal operating Pc & MR.

*Pump-fed min. ΔP_{inj} = 0.2 x Pc

**Includes 15 psi for ΔP across heat/exchanger (nozzle)

***Supercritical fuel cooling. Actual ΔPc.j. = 10 - 13 psi. Remaining ΔP is achieved across a throttling valve.

Pressure-fed OME and RCE ΔP_{inj}:

- Liquid injection: min. $\Delta P_{inj}/Pc$ = 0.2
- Gas injection: min. $\Delta P_{inj}/Pc$ = 0.15

Note: min. $\Delta P_{inj}/Pc$ occurs at low Pc and high MR corner of operating box.

TABLE XVII (cont.)

PRESSURE SCHEDULE - RCE

PROPELLANTS	LO_2/C_3H_8			LO_2/CH_4				COMMENTS
Pc/F	100/870	150/870	300/870	150/870				
• Plenum Pc, psia	100	150	300	150				
• Face Pc, psia (ox/fuel)	103	154	309	154				Based on Ac/At = 3.3
• ΔP_{inj}, psi *	54	28/82	163	30				Based on chug criteria
• ΔP_{TCV}, psi	20	20	20	20				Typical for exist engines
• ΔP_{lines}, psi	-	-	-	-				2% of Pc
• ΔP_{cj}, psi	-	-	-	-				
• $\Sigma\Delta$ P, psi	74	48/102	183	50				
• Interface or pump discharge pressure (ox/fuel) psia	177	202/256	492	204				
• $\Delta P_{inj}/Pc$	.54	.19/.55	.54	.20				
• $\Delta P_{cj}/Pc$	-	-	-	-				

CHAMBER THERMAL ANALYSIS - OME CONCEPTS

PROPELLANTS	LOX/C_3H_8	LOX/C_3H_8	LOX/C_3H_8	LO_2/C_3H_8	LOX/CH_4	LOX/CH_4	LOX/NH_3	COMMENTS
Pc/F	100/6K	150/.6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• Thrust, lbs	4500	4500	9000	5400	4500	9000	9000	
• Pc, psia	75	112.5	360	720	112.5	360	360	
• MR_{TCA}	3.30	2.14	2.94	3.15	4.08	3.68	1.28	
• MR_{Core}	3.30	3.30	2.94	3.15	4.08	3.68	1.47	
• $\dot{W}_{ox}$, lb/sec	10.23	8.94	19.00	10.95	10.47	19.76	15.96	
• $\dot{W}_f$, lb/sec	3.10	4.17	6.43	3.47	2.56	5.37	10.86	
• No.of Regen Passes	1	1	1	1	1	1	1	
• ΔPc.j., psi	5	76	11	132.8	15	8	63	
Pc.j.-in.psia	131	197	1200	1080	197	1200	630	
• Pc.j.out, psia	126	121	1189	947.2	182	1192	567	
• Tc.j.-in.°F	90	-44	-40	-44	-160	-259	-28	
• Tc.j.-out, °F	379	28	112	202	641	-82	12	
• ΔTc.j.,°F	289	72	156	246	801	177	40	
• Regen ε	6.23	6.23	10.64	23.76	6.23	10.64	6.73	Radiation cooled nozzle attachment area ratio
• $\dot{W}_{ffc}$, lb/sec	-	1.46	-	-	-	-	1.41	
• %Fuel Film Coolant	-	35	-	-	-	-	13.0	
• T_{ffc-in}, °F	-	28	-	-	-	-	126	
• Twg max, °F	802	161	787	949	1000	782	747	

Note: All thermal analyses were performed at low Pc and high MR corner of operating box. This is the most severe operating point.

ORIGINAL PAGE IS
OF POOR QUALITY

CHAMBER THERMAL ANALYSIS - OME CONCEPTS (cont.)

PROPELLANTS	LOX/C_3H_8	LOX/C_3H_8	LOX/C_3H_8	LOX/C_3H_8	LOX/CH_4	LOX/CH_4	LOX/NH_3	COMMENTS
Pc/E	100/6K	150/6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• Tw_1 max	800	144	744	780	995	739	160	
• h_g^*, BTU/in^2-sec-°F	.000371	.00193	.00262	.00477	.000995	.00262	.00368	
• h_1^* BTU/in^2-sec-°F	.00138	.00956	.0132	.0200	.00157	.0134	.0676	
• Tr^* °F	5346	1515	5740	5909	5346	5740	2233	
• Q/A_g max, BTU/in^2 sec	1.81	2.64	13.51	23.64	4.55	14.14	5.47	
• Q/A_1 max, BTU/in^2 sec	.40	1.41	6.37	11.97	1.03	5.70	6.25	
• $\frac{Q/A}{Q/A_{BO}}$ max.	-	.77	-	-	-	-	.454	
• Q Total, BTU/sec	186	170	584	554	526	1059	463	
• V_c max, ft/sec	155	51.8	47.2	106.9	309	39.8	111	
• V_c (Mach No)^{max}	.181	-	.014	.058	.177	.025	-	0.3 max
• No of channels**	323	263	207	112	263	206	208	
• Min Ch Depth, in	.082	.030	.084	.030	.040	.099	.050	.030 in. min.
• Limiting Criteria	T_{w1}	$\frac{Q/A}{Q/A\ B.O.}$	None	T_{w1}	T_{wg}	None	T_{wg}	
• Chamber Contraction Ratio	2.0	2.0	3.3	3.3	2.0	3.3	3.3	
• % Fuel Regen. Cooling	40	100	100	100	40	100	100	

* @ max-flux.
**At throat land width = .030" and channel width = .0325"

CHAMBER THERMAL ANALYSIS - RCE CONCEPTS

PROPELLANTS	LO_2/C_3H_8			LO_2/CH_4			COMMENTS
Pc	100	150	300	150			
• 870 Lb Thruster							Chamber I.D. = 3.9"
• Thrust, lbs	520	518	527	520			
• Pc, psia	60	90	180	90			
• MR_{TCA}	3.13	3.13	3.06	3.48			
• MR_{core}	3.85	3.85	3.85	4.20			
• $\dot{W}_{ox}$, lb/sec	1.624	1.263	1.220	1.291			
• $\dot{W}_f$, lb/sec	.518	.404	.399	.371			
• $\dot{W}_{ffc}$, lb/sec	.096	.076	.082	.064			Saturated vapor injection.
• % Fuel Film Coolant (of $\dot{W}_f$)	18.6	18.8	20.5	17.2			6% entrainment factor
• Taw Max, °F	2400	2400	2400	2400			2400°F maximum
• % Fuel Film Cool (of total flow)	4.5	4.5	5.0	3.8			
• 25 Lb. Thrusters							Concept is simil[illegible] to Lo_2/RP-1 igni[illegible] which has duct f[illegible] cooling. Core MR is 20:1 to reduc[illegible] Twg. Selected ov[illegible] all MR is at max Isp.
• Thrust, lbs							
• Pc, psia							
• MR_{TCA}							
• MR_{core}							
• $\dot{W}_{ox}$, lb/sec							
• $\dot{W}_f$, lb/sec							
• $\dot{W}_{ffc}$, lb/sec							
• %Fuel Film Coolant							
• Taw Max, °F							

ORIGINAL PAGE IS
OF POOR QUALITY

TPA AND GGA ANALYSIS - OME CONCEPTS (1 of 3)

PROPELLANTS	LO_2/C_3H_8		LO_2/CH_4	LO_2/NH_3	COMMENTS
Pc/F	400/10K	800/6K	400/10K	400/10K	
• Pumps					
• $\dot{W}_{ox}$, lbm/sec	20.9	12.1	22.0	16.9	
• $\dot{W}_f$, lbm/sec	7.9	4.3	6.4	14.0	
• $NPSP_{ox}$, psia	20.3	20.3	41.3	34.3	
• $NPSP_f$, psia	20.3	20.3	20.3	20.3	
• P_{iox}, psia	35.0	35.0	56.0	49.0	
• P_{if}, psia	35.0	35.0	35.0	35.0	
• P_{Dox}, psia	535	1020	535	533	
• P_{Df}, psia	980	1196	980	614	
• T_{sox}, °R	162.7	162.7	162.7	162.7	
• T_{sf}, °R	416.2	416.2	217	432	
• Spec. Spd_{ox}	2920	1740	4920	4360	
• Spec SPd_f	1315	1140	1130	3150	
• Suct.Spec. Spd_{ox}	30K	30K	30K	30K	
• Suct.Spec Spd_f	30K	23K	36K	36K	
• No. of $Stages_{ox}$	1	1	1	1	
• No. of $Stages_f$	1	1	1	1	

ORIGINAL PAGE IS
OF POOR QUALITY

TPA AND GGA ANALYSIS - OMF CONCEPTS (2 of 3)

PROPELLANTS	LO_2/C_3H_8		LO_2/CH_4	LO_2/NH_3	COMMENTS
Pc/F	400/10K	800/6K	400/10K	400/10K	
• Imp. D_{ox}, in	1.48	1.46	1.00	0.96	
• Imp. D_f, in	1.60	1.40	1.80	1.30	
• η_{ox}, %	61.9	59.6	56.4	55.4	
• η_f, %	59.5	56.6	59.0	59.0	
• Turbines					
• Pin, psia	390	790	390	390	
• Pout, psia	39	79	39	39	
• Pr	10	10	10	10	
• $\dot{W}_{GG_{ox}}$, lbm/sec	0.22	0.24	0.15	0.14	for Ox TPA
• $\dot{W}_{GG_f}$, lbm/sec	0.26	0.19	0.23	0.24	for Fuel TPA
• T_{in}, °R	2000	2000	2000	2000	
• $Tout_{(ox, fuel)}$ °R	1682/1603	1646/1628	1565/1579	1539/1515	
• ΔT, °R	318/397	354/372	435/421	461/485	
• Spec. Spd_{ox}	8	7.5	9.4	9.7	
• Spec Spd_f	19	10	17.0	13.3	
• No. of $Stages_{ox}$	1	1	1	1	
• No. of $Stages_f$	1	1	1	1	
• Tip D_{ox}, in	5.1	5.4	4.7	4.7	
• Tip D_f, in	4.1	3.9	3.9	4.4	
• η_f, %	69	65	62	68	
o η_{ox} %	55	62	64	64	

ORIGINAL PAGE IS
OF POOR QUALITY

TPA AND GGA ANALYSIS - OME CONCEPTS (3 of 3)

PROPELLANTS	LO_2/C_3H_8		LO_2/CH_4	LO_2/NH_3	COMMENTS
Pc/F	400/10K	800/6K	400/10K	400/10K	
• Gas Generator					
• Pc_{GG}, psia	400	800	400	400	
• $\dot{W}_{GG_{ox}}$, lbm/sec	0.22	0.24	0.15	0.14	
• $\dot{W}_{GG_f}$, lbm/sec	0.26	0.19	0.23	0.24	
• MR	0.36	0.36	1.2	0.57	
• Cp, BTU/lbm-°F	0.64	0.64	0.78	0.69	
• γ	1.18	1.18	1.23	1.25	
• MW	20	20	13.5	16.6	
• Tc, °R	2000	2000	2000	2000	
• Additional Data					
Pumps:					
• Oxid Flow, GPM	132	76	138	106	
• Fuel Flow, GPM	134	53	109	165	
• Oxid Speed, RPM	45,070	59,200	72,600	72,600	
• Fuel Speed, RPM	84,500	87,250	87,250	77,500	
• Impeller Tip Spd.					
• Oxid, ft/sec	291	377	317	304	
• Fuel, ft/sec	590	533	686	440	
• Shaft Power					
• Oxid, HP	64	76	71	54	
• Fuel, HP	94	66	106	95.4	
Turbine:					
• Blade Tip Spd (u)					
• Oxid, ft/sec	1,000	1400	1500	1500	
• Fuel, ft/sec	1,500	1500	1500	1500	
• Ratio u/spouting velocity (u/v)					
• Oxid	0.23	0.32	0.29	0.32	
• Fuel	0.34	0.34	0.29	0.32	

TABLE XVII (cont.)

PERFORMANCE ANALYSIS - OME CONCEPTS

PROPELLANTS	LO_2/C_3H_8				LO_2/CH_4		LO_2/NH_3	COMMENTS
Pc/F	100/6K	150/6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• Engine Fv, lbf	6000	6000	10,068	6,061	6000	10,062	10,064	
• TCA Fv, lbf	6000	6000	10,000	6,000	6000	10,000	10,000	
• Engine MR	2.75	1.79	2.69	2.81	3.40	3.44	1.21	
• TCA MR	2.75	1.79	2.80	3.00	3.40	3.50	1.22	
• Core MR	2.75	2.75	2.80	3.00	3.40	3.50	1.40	Max ODK Isp MR
• Film Barrier MR	-		-	-	-	-		
• Turbine Ex. Fv, lbf	-	-	68	61	-	62	48	
• TCA $\dot{W}_{Tot}$, lbm/sec	17.80	18.37	28.15	16.01	17.33	27.88	30.41	
• TCA $\dot{W}_{ox}$, lbm/sec	13.05	11.79	20.74	12.01	13.39	21.68	16.71	
• TCA $\dot{W}_f$, lbm/sec	4.75	6.58	7.41	4.00	3.94	6.20	13.70	
• $\dot{W}_{turb}$, lbm/sec	-	-	.48	.43	-	.38	.38	
• % Fuel Film Coolant (of fuel flow)	0	35	0	0	0	0	13	
• Eng $\dot{W}_{ox}$, lbm/sec	13.05	11.79	20.87	12.12	13.39	21.89	16.85	
• Eng $\dot{W}_f$, lbm/sec	4.75	6.58	7.76	4.32	3.94	6.37	13.94	
• Eng Isp, Sec	337.0	326.7	351.7	368.7	346.2	356.0	326.5	
• TCA Isp, sec	337.0	326.7	355.2	374.7	346.2	368.7	328.8	
• Core Isp (ODK), sec	350.7		371.6	394.1	360.8	375.9		
• ISP_{turb}, sec	-	-	141.8	141.8	-	164.3	141.2	
• Ae/At	46	67	115	404	69	115	111	
• D_t, in.	6.34	5.26	4.02	2.14	5.12	4.00	4.14	
• D_e, in	43	43	43	43	43	43	43	
• % Fuel Film Coolant (of total flow)	0	12.5	0	0	0	0	5.8	
• Engine Total Flow Rate, lbm/sec	17.80	18.37	28.63	16.44	17.33	28.26	30.79	

TABLE XVII (cont.)

PERFORMANCE ANALYSIS - RCE CONCEPTS

PROPELLANTS	LO_2/C_3H_8			LO_2/CH_4			COMMENTS
Pc	100	150	300	150			
• 870 lbf Thrusters							
• TCA MR	2.24	2.23	2.19	2.48			Max ODK Isp MR
• Core MR	2.75	2.75	2.75	3.00			
• TCA $\dot{W}_{ox}$, lbm/sec	2.02	1.97	1.87	1.97			
• TCA $\dot{W}_f$, lbm/sec	.90	.88	.86	.80			
• % $\dot{W}_{ffc}$ (of fuel flow)	18.6	18.8	20.5	17.2			
• TCA Isp, Sec	297.9	306.6	318.8	313.9			
• Core Isp(ODK), sec							
• Ae/At	18	27	56	27			
• D_t, in	2.52	2.04	1.42	2.02			
• D_{ex}, in	10.6	10.6	10.6	10.6			
• 25 lbf Thrusters							
• TCA MR	2.75	2.75	2.75	3.00			
• Core MR	20	20	20	20			
• TCA $\dot{W}_{ox}$, lbm/sec	.082	.080	.077	.080			
• TCA $\dot{W}_f$, lbm/sec	.030	.029	.028	.026			
• % $\dot{W}_{ffc}$ (of fuel flow)	23	23	23	21			
• TCA Isp, sec	223.4	229.2	239.1	235.4			
• Core Isp(ODK), sec	-	-	-	-			
• Ae/At	18	27	56	27			
• D_t, in	.42	.35	.24	.35			
• D_{ex}, in	1.80	1.80	1.80	1.80			

*Film cooling as % of total flow

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XVII (cont.)

WEIGHT (LBM) - OME CONCEPTS

PROPELLANTS	LO_2/C_3H_8				LO_2/CH_4		LO_2/NH_3	COMMENTS
Pc/F	100/6K	150/6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• TCA (each)								
. Injector	19.6	14.0	15.7	4.6	13.2	15.6	16.8	
. Chamber	77.6	52.9	65.3	36.8	58.2	57.4	47.9	
. Nozzle	79.5	78.0	79.5	85.6	77.1	79.1	81.6	
. Controls+TCA Instr.	18.3	18.3	19.3	19.3	18.3	19.3	19.3	Does not include TCA valve
	195.0	163.2	179.8	146.1	166.8	171.4	165.6	
• Thrust Structure Assy.	21.3	21.3	30.5	21.3	21.3	30.5	30.5	Scaled from OME
• Gimbal System	52.9	52.9	74.4	52.9	52.9	74.4	74.4	Scaled from OME
• Plumbing**	21.7	17.2	18.2	16.9	17.2	18.2	18.2	
• TPA (ox/fuel)*	-	-	10.2/6.5	11.8/5.5	-	7.6/6.5	7.6/5.9	
• Boost Pump(ox/fuel)	-	-	-	-	-	-	-	
• GGA (ox/fuel)*	-	-	2.4/2.6	2.3/2.3	-	2.4/2.6	2.4/2.4	
• Controls & Instr.								
. TCA Valve	21.0	21.0	21.0	21.0	21.0	21.0	21.0	
. Pneumatic Pack	7.6	7.6	7.6	7.6	7.6	7.6	7.6	
. Purge Valves	-	-	-	-	-	-	-	Not required
. Instr.*	2.6	2.6	9.6	9.6	2.6	9.6	9.6	
. GGA Valves*	-	-	7.8	7.8	-	7.8	7.8	
. TPA Controller*	-	-	22.8	22.8	-	22.8	22.8	
. Boost Pump* Circuit Valves	-	-	-	-	-	-	-	
	31.2	31.2	68.8	68.8	31.2	68.8	68.8	
Total, lbm	322.1	285.8	393.4	327.9	289.4	382.4	376.8	

*For two TPA's double these weights

**Plumbing weights are for TCA only. They do not include: Purge lines, GGA lines, or turbine exhaust/duct lines. These weights for pump-fed OME point designs previously supplied are: 2.6#, 2.0#, and 10.0# respectively.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XVII (cont.)

WEIGHT (LBM) RCE CONCEPTS

PROPELLANTS	LO_2/C_3H_8			LO_2/CH_4			COMMENTS
Pc	100	180	300	180			
• 870-lbf Thruster							
• TCA (each)							
. Valves	2.6	3.4	2.6	5.3			
. Injector	6.4	5.3	3.9	5.3			
. Chamber/Nozzle	4.8	4.8	4.8	4.8			
. Insulation + Misc.	9.4	9.4	9.4	9.4			
	23.1	22.9	20.6	24.8			
• Propellant Conditioning							
. Heat Exchanger (ox/fuel)		26.3/-		26.3/26.5			
. GGA (ox/fuel)		5.5/-		5.5/4.5			
		31.8		62.8			
• Controls & Instr.							
. Pressure Reg. (ox/fuel)		6.2/2.0		6.2/6.2			
. Accumulator Valves (ox/fuel)		7.6/3.8		7.3/7.3			
. TPA GGA Valves		7.8		7.6			
. Prop.Cond GGA valves		3.3		10.9			
. Main Propellant valves(ox/fuel)		4.3/3.8		4.2/4.9			
. Instr.		14.4		19.2			
. TPA Controller		36.0		36.0			
		89.2		109.8			

ORIGINAL PAGE IS
OF POOR QUALITY

ENVELOPE/SIZE - OME CONCEPTS

PROPELLANTS	LOX/C_3H_8			LO_2/CH_4			COMMENTS
Pc	100	150	300	150			
• 25-lbf Thruster TCA (each)	W_B (~8.0 lbm)	W_B+0.5	W_B	W_B+1.0			W_B is notation for the basic 25-lbf thruster weight which is 6-10 lbm Deviations shown reflect valve weight differences

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XVII (cont.)

ENVELOPE/SIZE - OME CONCEPTS

PROPELLANTS	LO_2/C_3H_8				LO_2/CH_4		LO_2/NH_3	COMMENTS
Pc/F	100/6K	150/6K	400/10K	800/6K	150/6K	400/10K	400/10K	
• TCA (each)	-	-	-	-	-	-	-	Same as existing TCA (approx 77" x 46")
. Length, in.								
. Nozzle Dia.in								
• TPA (ox/fuel)								
. Length, in.	-	-	6	6	-	6	6	
. Diameter, in.	-	-	8	8	-	8	8	
• GGA(ox/fuel)								
. Length, in.	-	-	10	10	-	10	10	
. Diameter, in	-	-	4	4	-	4	4	

ENVELOPE/SIZE - RCE CONCEPTS

PROPELLANTS	LOX/C_3H_8			LO_2/CH_4			COMMENTS
Pc	100	150	300	150			
• 870 Lbf Thruster	-	-	-	-			Same as existing TCA's(approx. 19" x 11")
• 25 Lbf Thruster	-	-	-	-			Same as existing TCA's(approx. 11" x 6")
• Heat Exchangers (ox/fuel)							
. Length, in	-	20		20			
. Diameter, in	-	12	-	12			
• GGA's (ox/fuel)							
. Length, in	-	11.0/-	-	11.0/11.0			
. Diameter, in.	-	5.1/-	-	5.1/4.3			

ORIGINAL PAGE IS
OF POOR QUALITY

HEAT EXCHANGER AND GGA ANALYSES

PROPELLANTS	LOX/C_3H_8			LOX/CH_4			COMMENTS
Pc	100	150	300	150			
				OX	FUEL		
• $\dot{W}_C$, lbm/sec	21	21		21	6		
• T_{C_i}, °R		162		162	200		
• T_{C_o}, °R		310		310	380		
• P_{C_i}, psia		900		900	900		
• P_{C_o}, psia		800		800	800		Judgment
• $\dot{W}_H$, lbm/sec		3.4		2.9	1.6		
• T_{H_i}, °R		2000		2000	2000		Fuel rich GGA
• T_{H_o}, °R		800		800	800		Judgment
• P_{H_i}, psia		600		600	600		"
• P_{H_o}, psia		300		300	300		"
• ΔQ_C, Btu/sec		2,184		2,184	1,200		
• % η		80		80	80		Assumption
• $\dot{W}_H/\dot{W}_C$		0.16		0.14	0.27		